Experiments in Atomic Physics

FRIEDRICH · LANGEHEINE · ULBRICHT

Experiments in Atomic Physics

FRIEDRICH · LANGEHEINE · ULBRICHT

Experiments in Atomic Physics

A. FRIEDRICH · H. LANGEHEINE · H. ULBRICHT

JOHN MURRAY 50 ALBEMARLE STREET LONDON

Printed in Great Britain by Butler & Tanner Ltd, Frome and London

Foreword

In 1958 the Physics Panel of the Science Masters' Association and the Association of Women Science Teachers (now combined as the Association for Science Education) began its task of reviewing the position of physics teaching in Grammar Schools and making recommendations for reform and modernization. Very soon we had to face up to the problem of the extent to which we could recommend that modern Atomic Physics should be included in a school course. Information reached us that this section of Physics was already being extensively taught in West German schools, but largely by demonstration lessons, with students' laboratory work playing a very small part. Not long afterwards two German instrument manufacturers began to introduce into this country some remarkable, and expensive, demonstration apparatus.

This book has been translated from the German by a very well-known member of A.S.E. When a proof copy was sent to me I expected to find a collection of demonstration experiments based on the above-mentioned apparatus. It was with considerable surprise that I found that many of the experiments used improvised apparatus (*vide* the section on cloud chambers), and many were essentially suitable for individual pupils or small groups of pupils to perform.

A number of the experiments are familiar to British teachers: some have been our stock-in-trade for many years and others resemble those described in the pages of the *School Science Review*; but many are new to most of us—either completely new or with a new slant. The chief attraction of the book, however, is in the sequential arrangement which suggests a satisfying logical development. There is a main theme with some relevant asides.

After the publication of *Physics for Grammar Schools* (1961) we were confronted by a number of highly placed critics who maintained that 'Modern Physics' could not be taught in schools in an educationally satisfying manner but only didactically and with much 'chalk and talk'. It is a pity that this book—based upon the German of 1960—was not then available.

Harold Tunley
Chairman of the Physics Panel
Association for Science Education

August 1965

Preface

This book is a translation from a West German one entitled *Versuche zur Atomphysik*, which consists of experiments selected by three German science masters from the pages of the periodicals *Praxis*, *Der Mathematische und Naturwissenschaftliche Unterricht* (referred to as M.N.U.), *Praschu*, and others. It therefore resembles the British *Science Masters' Books*, which contain experiments selected from the *School Science Review*. It differs from these last in that it deals with only one branch of physics, and that the instructions are generally shorter, so leaving a good deal to the ingenuity of the reader in interpreting them. Like the *Science Masters' Books*, it is intended mainly for teachers and is not a textbook for students. References are given to original articles; this saves long descriptions, though it may appear that details and precautions are sometimes lacking. The diagrams are given as guides, and may be even rough sketches; it is left to the reader to find the best arrangement with his own apparatus. The experiments, as is customary in Germany, are often demonstrations by the teacher, but many of them could be fairly easily adapted for class use. The emphasis is largely on 'make it yourself'.

The German sections dealing with safety precautions have been replaced by the corresponding British ones. The experiments dealing with neutrons, prohibited in all but a very few British schools, have been retained since they may be of interest in some institutions for education beyond school standard.

Some of the experiments described in the book are variants on ones that have appeared independently in the *School Science Review*. It may be found helpful to consult past numbers of this for additional information on any particular subject; this may easily be done by the help of Mr D. H. J. Marchant's excellent *Index to the SSR.*, obtainable from the Headquarters of the Association for Science Education at Cambridge.

Contents

1
Spectra

Continuous spectra

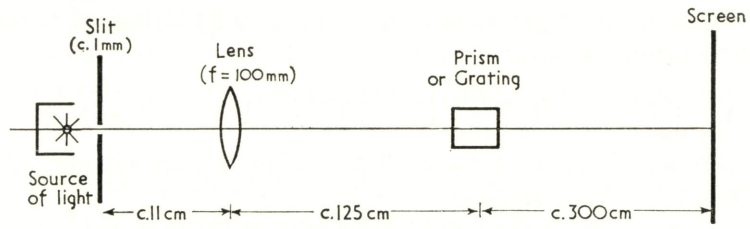


Fig. 1.1

Expt. 1 (fig. 1.1). A slit is first focussed sharply on a screen. Then a direct vision prism or diffraction grating is placed in the path of the light beams. As sources of light one may use electric bulbs, arc lamps, or sunshine (Bredemeier, PRAXIS, 1952/6, p. 164).

U.V. spectrum

Expt. 2. A strip of graph paper is painted with phosphorescent zinc sulphide length-wise along its upper half. If this paper is then held in a spectrum, the visible spectrum will be seen on the lower half of the paper. If the paper is now taken away from the spectrum, the extent of the u.v. spectrum can be seen by the still-continuing phosphorescence. With a u.v. filter one may obtain the u.v. spectrum alone.

Line spectra

Expt. 3. Hydrogen spectrum. If a eudiometer is filled with hydrogen and sparks are allowed to pass for some time, the gas gives out light. If a slit is placed close to the eudiometer and is viewed through a direct vision spectroscope, a number of narrow lines are seen, particularly red, green, blue, and a number of violet ones. The frequencies agree with those calculated from the Balmer equation, if $n = 2$ and $m = 3, 4, 5, 6$. This equation is

$$\nu = \left(\frac{1}{n^2} - \frac{1}{m^2}\right) \times 3{\cdot}29 \times 10^{15}\ \text{sec}^{-1}$$

Expt. 4. Line spectra are obtained most easily if, instead of the eudiometer, one uses:

(i) Geissler tubes containing different gases;
(ii) gas-filled glow lamps, e.g. neon;
(iii) bunsen flames coloured with salts of lithium, sodium, calcium, and other elements;
(iv) an arc lamp having the above salts on the carbons;
(v) an arc lamp with a carbon replaced by rods of copper, iron, or other metals;
(vi) an induction coil, with wires of copper, iron, aluminium, etc., connected to the secondary terminals. If sparks are obtained between the wires, very lovely spark spectra, with many lines from red to violet, occur.

Expt. 5. If the spectra are to be shown on a screen, the low intensity of the image on the screen requires that the source of light shall be of maximum intensity. A mercury vapour lamp, enclosed save for a slit in the screen, gives a line spectrum in a darkened room.

Instructions for exercises in spectroscopy

Expt. 6. A screen with dull black cloth stretched across it has a strip of shiny white paper about 3 mm wide fixed vertically down the middle. This is illuminated with bright sodium or mercury light. If the strip is observed through a prism with the refracting

edge parallel to the strip, the corresponding spectral lines will be seen (Schlee, PRASCHU, 1949, p. 88).

Expt. 7. The strip of paper may be replaced by a strip of metal polished with a piece of fine emery cloth (or by a nickel-plated rod, the bulb of a clinical thermometer, or a knitting needle). The wider the strip, the brighter the spectrum becomes; the thinner it is, the sharper are the lines (especially the Fraunhofer lines). The observer must be shielded from direct light from the source.

Additional experiments—observations with prism or grating

(i) The strip is illuminated by means of an electric lamp. It is demonstrated that if the lamp is slowly made brighter the spectrum builds up from the red end, and that if the lamp is slowly extinguished the spectrum fades away first from the violet end.
(ii) If the strip is illuminated by a continuous spectrum, one can ascertain that none of the colours can be split up further.
(iii) If the spectrum is not wide enough or not sharply enough focussed on the strip, the neighbouring colours appear also.
(iv) In sodium light the sodium lines are seen.
(v) With the carbons used in Expt. 8 one can show many spectral lines.
(vi) By using sunlight one can show the Fraunhofer lines by means of a good prism or grating.

(Krum, PRASCHU, 1949, p. 211)

Reversal of spectral lines

Expt. 8. An arc lamp is used with carbons at right angles (most simply, two retort stands with thin carbons as shown in Fig. 1.2[1]), the horizontal carbon being the thinner one. This is arranged above the thicker vertical one, which has been treated with a sodium salt (or corresponding lithium, calcium, or barium salts). The carbons are connected to a d.c. source of 40 to 60 volts. In front is placed, as usual, a screen with a slit, and when a prism is placed in the path of the light, a continuous spectrum is obtained on the screen. The yellow sodium line (or the lithium,

[1] The arrangement shown is purely diagrammatic: the carbons should be in a proper arc lamp so that there is no risk of touching them. The arc should not be handled by pupils.

calcium, or barium line) is especially bright. If the d.c. connections are reversed the light has to pass through the cloud of vapour. On the screen deep black lines are seen in the spectrum instead of the previous bright ones. If the current reversal is made quickly enough, so that the vapour cloud is still present, the effect can be repeated as often as one likes.

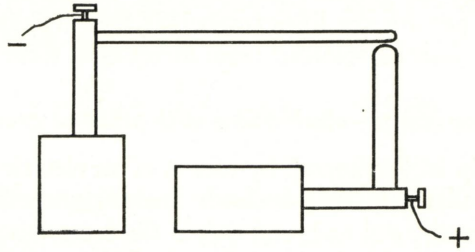


Fig. 1.2

Preparation of the carbons. Bring the anode to brightness in the arc: take it out with pliers and immerse it in a saturated solution of a sodium, lithium, calcium, or barium salt (Wolf, UBL, 1930, p. 320; PRASCHU, 1951, p. 172).

Expt. 9 (fig. 1.3). A slit illuminated by a 12-volt lamp bulb is projected on to a screen by means of a lens. Somewhat below the

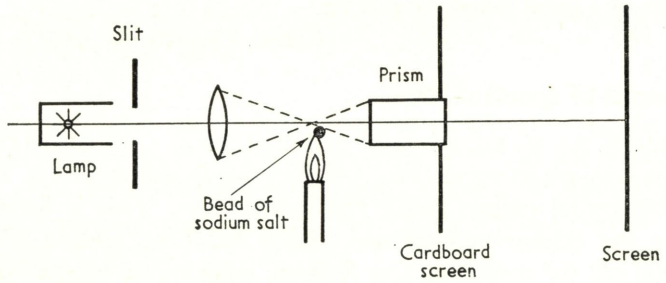


Fig. 1.3

narrowest part of the beam of light a bead of a sodium salt is placed (dry soda) and a direct vision prism is put near it in the beam of light. The bunsen burner is now brought up to the bead, with a small non-luminous flame; then in a short time the absorption spectrum will be seen. The prism should be surrounded by a large

cardboard screen, so as to block out unnecessary light (Stöckel, MNU, III/5, p. 312).

Note. In all experiments on absorption spectra, care should be taken that the bead of salt is on the prism side of the flame so as to avoid effects due to the uncoloured part of the flame.

Expt. 10. Light from an arc lamp is focussed by means of a condenser lens so that the narrowest part of the emergent beam passes

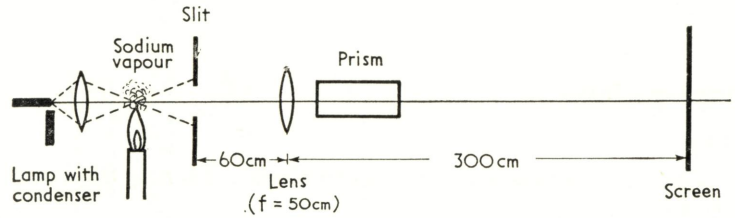


Fig. 1.4

through a bunsen flame into which a sodium nitrate bead is introduced by means of a magnesia rod. The beam then passes through a slit, a sharp image of which is formed on a distant screen by means of a convex lens of focal length about 50 cm. A direct vision prism is placed near the lens, on the side towards the screen. If the distance from slit to lens is about 60 cm, and that from lens to screen 300 cm, then the dark sodium absorption lines should be visible in the continuous spectrum produced on the screen. The adjustment is rather critical (Mirow, PRAXIS, 1952/1, p. 12).

Expt. 11. In an experiment due to Kröncke the light of a sodium lamp is thrown on to a white screen without any further optical arrangement. A non-luminous bunsen flame is placed in the path of the light. If this flame is now coloured yellow by means of a sodium salt, a dark shadow of the flame will appear on the screen (Keutel, PRAXIS, 1954/5, p. 155).

Expt. 12. A beam of sunlight is passed through a narrow slit. A prism with high dispersive power, e.g. a CS_2 prism, will then show the Fraunhofer lines.

2
Electrolytic ionization in liquids and gases

Faraday's laws

Law 1

(*a*) *The mass liberated is directly proportional to the time, the current being constant.*

Expt. 13. A Hofmann's voltameter[1] is filled with dilute sulphuric acid: the quantity of gas produced in equal intervals of time by a constant current is determined.

(*b*) *The mass liberated is directly proportional to the current, the times being constant.*

Expt. 14. With apparatus as in Expt. 13, the strength of the current is changed each five minutes so as to be $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, 1 amp and so on, and the volume of gas liberated is noted.

The mass liberated is directly proportional to the quantity of electricity.

Expt. 15. The Hofmann apparatus is filled in turn with electrolytes of different concentrations and different compositions (e.g. NaOH and H_2SO_4 produce equal quantities of hydrogen and of oxygen) through which equal currents are passed for equal times.

[1] If carbon electrodes are used, the apparatus must be set going about half an hour before it is needed, since hydrogen is absorbed by the electrodes. However with platinum electrodes the determination of the oxygen is possible only if the apparatus has already been in action for half an hour, since the solubility of hydrogen in water is at first much less than that of the oxygen.

Law 2

The mass liberated is directly proportional to the chemical equivalent weight of the element.

Expt. 16 (fig. 2.1). An accurately determined current is passed through the following apparatus arranged in series:

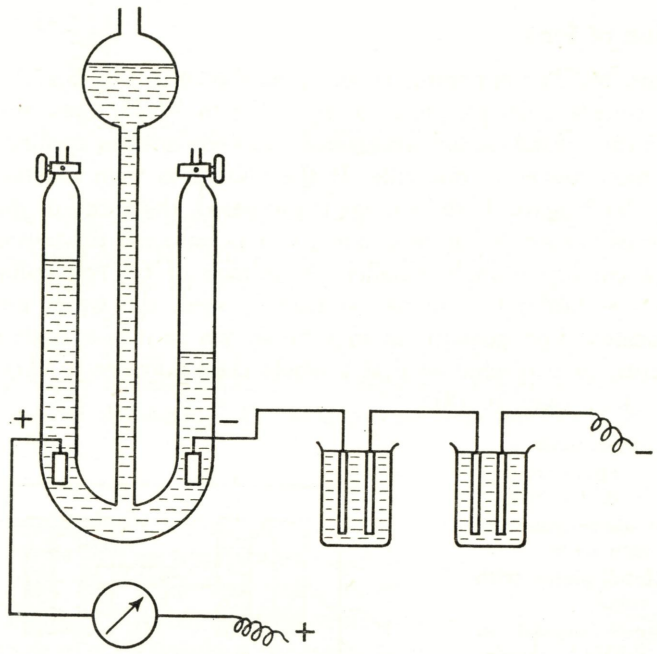


Fig. 2.1

Hofmann's apparatus with dilute H_2SO_4.
Beaker with $CuSO_4$ solution and copper electrodes.
Beaker with $AgNO_3$ solution and platinum electrodes.

The volumes of hydrogen and oxygen produced are measured, and the copper and silver liberated are weighed. From these are calculated:

(i) *The equivalent weight.* The mass of the liberated hydrogen is calculated by means of the gas laws and the density, and is divided into the masses of the other substances.

(ii) *Faraday's number.* By means of Faraday's first law, the

mass liberated by 1 amp in 1 sec is calculated; the equivalent weight is divided by this weight. E.g. for silver, 107·8 ÷ 0·001118 = 96 500 coulombs.

(iii) *The electronic charge.* The electronic charge is obtained from Faraday's number and Avogadro's number. E.g. 96 500 coulombs ÷ $6 \times 10^{23} = 1{\cdot}6 \times 10^{-19}$ coulomb.

Motion of Ions

Expt. 17. The apparatus is set up as shown in Fig. 2.2. After a short time a small purple coloration due to MnO_4 ions appears round the crystal. A d.c. voltage of 100 volts is then applied: the coloration moves to one side. If the voltage is then reversed, it moves back again. If the voltage is increased, the speed of motion of the coloration becomes greater; if it is reduced, the speed becomes correspondingly smaller. A voltage of 60–100 volts has proved suitable: if a higher voltage is used, the water quickly evaporates. The experiment may be shown as it is to individual students, or projected so that a whole class may see it (Krumm, PRASCHU, 1949, p. 181).

(1) Plate of glass
(2) Filter paper soaked in KNO_3 soln.
(3) Strips of glass 3–5 mm wide
(4) Metal plates with wires
(5) Small crystal of $KMnO_4$ under the strips of glass
(6) KNO_3 soln.

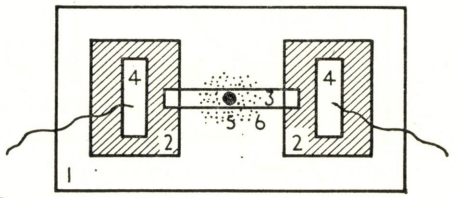


Fig. 2.2

The difference in velocities of diffusion of different kinds of ions may be shown by the following experiment:

Expt. 18. A strip of filter paper soaked in concentrated KCl solution is placed on a microscope slide, and has at each end a small piece of metal as an electrode. The metal, paper, and slide are held together by crocodile clips. Small crystals of potassium permanganate, potassium bichromate and copper sulphate are now placed at the middle of the filter paper, about 0·5 cm apart. A voltage of

about 70 volts is applied; the different velocities of each kind of ion can then be seen. The differences may even be estimated quantitatively (Marthaler, PRAXIS, 1957/1, p. 6).

Expt. 19. Two thistle funnels are bent at right angles, as shown in Fig. 2.3, and joined by rubber tubing. About one third of each

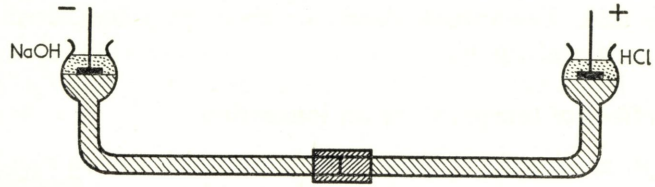


Fig. 2.3

tube is filled with a solution made up from 1 g of gelatin and 2 g of NaCl in 50 cm^3 of distilled water; this is coloured violet with litmus. When this solution has set, the remainder of one tube is filled with dilute NaOH and the remainder of the other with dilute HCl. The negative electrode is immersed in the NaOH, and the positive one in the HCl; the voltage is adjusted so as to give a potential difference of about 1 volt per cm along the tube (Arrhenius).

Expt. 20 (fig. 2.4). The thistle funnel is filled, as far as the junction with the U-tube, with a 1 : 500 solution of $KMnO_4$ which has about 5 g of urea added to each 100 cm^3. The $KMnO_4$ solution must not enter the U-tube. Bubbles of air in the tube may be removed by means of a wire. The U-tube is then filled to a height of about 5 cm with a very dilute solution of KNO_3. Then the tap is cautiously opened so as to allow the $KMnO_4$ solution to rise slowly into the U-tube until the electrodes are about 1 cm below the level of the KNO_3 solution. A voltage of 20 to 40 volts is then applied to the electrodes, and the movement of the top surface of the MnO_4 ions towards the anode is observed at intervals (Nernst).

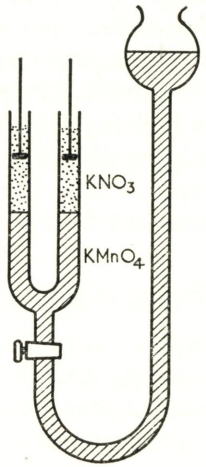


Fig. 2.4

Expt. 21. Copper sulphate and potassium bichromate are ground up together with fine silica powder in a mortar: the mixture is put in a U-tube which is topped up on either side with pure silica powder. Then small quantities of dilute sulphuric acid are poured alternately into the two sides so that the powder is saturated and the acid stands about 1 cm above it. The electrodes are immersed in the acid. The voltage should be about 70 volts (Marthaler, PRAXIS, 1957/1, p. 6).

The effect of temperature on ionization

Expt. 22. A strip of glass about 5 mm thick and 20 mm long has two wires each about 60 mm long and 1·5 mm thick sealed into its ends to act as electrodes; or crocodile clips may be used. A voltage of 220 volts is applied to the strip through a resistance of 5 ohms and an ammeter reading up to 30 amps. No current will flow. The glass is now carefully heated with a bunsen burner; when it is red hot a small current begins to flow. As the temperature increases, this quickly grows larger. The heating now produced by the electric current causes a still further increase in temperature, so that the glass melts and drips down, even if the bunsen burner has been removed. A sheet of metal or asbestos should be put so as to catch the drops of glass.

Herr H. Mittag, in PRAXIS, 1958/7, p. 189, gives an easy and striking way of demonstrating this experiment:

Two carbon arc rods of about 5 mm diameter are fixed horizontally in clamps so that their ends are 0·5–1 cm apart; the gap between them is bridged by a piece of glass tubing. A 200-watt lamp bulb is put in the circuit both as a protective resistance and as a current indicator. As the tubing is heated with a bunsen burner, the lamp begins to light up, and continues to get brighter without any further heating of the glass.

Diffusion of ions through glass

Expt. 23. A 15- or 25-watt lamp bulb of clear glass is connected to 220 volts d.c. The positive terminal is connected through a resistance of about 1000 ohms and a milliammeter reading to 50 mA with an iron bowl in which sodium nitrate is heated up to 300° C so that it melts. The lamp bulb is now carefully lowered into the

molten salt: the milliammeter shows a current. Electrons flow from the filament through the glass to the salt, and sodium ions from the salt to the filament. Inside the bulb most of the sodium ions are neutralized by electrons, and condense on the cold inside of the bulb as metallic sodium. The remainder move to the filament together with any positive gas ions already present: they cause additional heating and great brightness of the filament. If the connection between the positive terminal and the iron bowl is broken, the brightness of the filament decreases (Saur, PRAXIS, 1956/11, p. 293).

Ionization

(*a*) *Ionization by flames*

Expt. 24. A charged electroscope will hold its charge for a long time, but if a lighted candle, a burning splinter, or a bunsen flame are brought near it, the charge is lost quickly.

Expt. 25. Two platinum electrodes are placed about 2 mm apart, and are put in series with a sensitive ammeter and a protective resistance: a voltage of about 100 volts is applied to the circuit. When the electrodes are heated in a flame, a current passes between them.

(*b*) *Ionization by irradiation*

Expt. 26. (i) The apparatus is as in the last experiment. The current flows when Röntgen rays pass between the electrodes.

(ii) If the X-ray tube is turned off, the leaves of the electroscope at once stay as they are. If it is turned on and off alternately, the leaves converge in jumps.

(*c*) *Ionization by radioactivity*

Expt. 27. (i) The apparatus is as in Expt. 24. This time the current flows when a radioactive source is brought near.

(ii) The experiment may be varied by altering the distance and then determining the rate of fall of the leaves; the radioactive source may also be covered with paper, cellophane, or metal foils so as to vary the radiations.

3
Radiation: laws of waves and particles

Polarization of X-rays

Expt. 28 (fig. 3.1). The broad cone of X-rays from an ordinary demonstration X-ray bulb is reduced by lead screens to a small

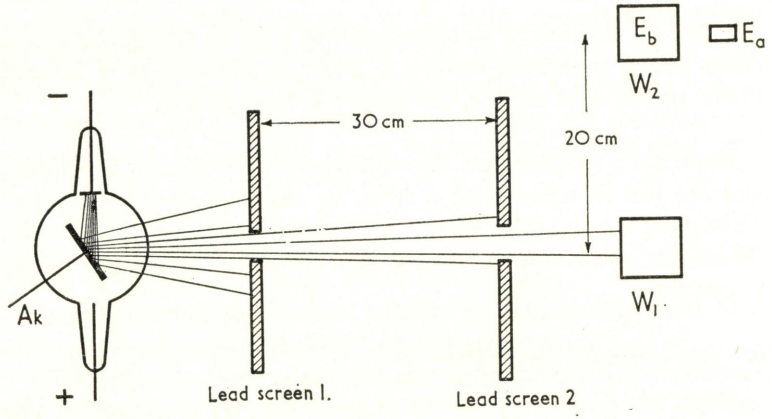


Fig. 3.1

beam of about 4 cm² cross-section: this is directed on to a cube of paraffin of side about 5 cm. X-rays are assumed to be transverse waves; then the carbon and hydrogen atoms hit by them are excited in such a way that the secondary rays going from W_1 to another paraffin block W_2 are polarized at right-angles to the plane of the diagram. W_2 must be shielded from radiation coming directly from the X-ray bulb. The intensity of the tertiary rays coming from W_2, measured with a suitable receiver, e.g. a Geiger tube or point counter, must also be greater in the direction E_a in the plane of the paper than in the directions E_b at right-angles to that plane and either going into or coming out of it. The result of the experiment proves the truth of the assumption that X-rays are trans-

verse. The fact that a certain intensity is also found in the direction E_b is due to the production of non-polarized Compton waves (Buhl, PRASCHU, 1955/9, p. 132).

Diffraction by gauze as a substitute for Laue's experiment

Expt. 28a. A screen with a hole in it about 2–3 mm in diameter is illuminated with an arc lamp and projected on to a screen by means of a lens. If fine gauze or some silk material is placed immediately behind the lens, an interference pattern is produced, which consists of regularly arranged points.

Theory of light quanta

As a proof that the wave theory is not sufficient for the explanation of all phenomena in light, the following experiments may be performed.

Expt. 29. A mercury vapour lamp, a lens, and a sensitive neon lamp are arranged on an optical bench. The voltage applied to the neon lamp is adjusted so that the lamp just does not light. When the neon lamp is exposed to rays from the mercury lamp it lights up since the photoelectrons emitted are sufficient to reach the striking voltage. If yellow or green filters are put in the path of the rays, this effect does not occur; but it does with blue or violet filters.

Instead of the lighting-up of a neon lamp, clicks in a loudspeaker may be used as an indicator (PRAXIS, 1956/4, p. 87, which refers to Dr Hecht of Cologne, and Dr Ristau of Hamburg, who first devised this experimental method).

Expt. 30 (fig. 3.2). The yellow, green, violet, and ultra-violet

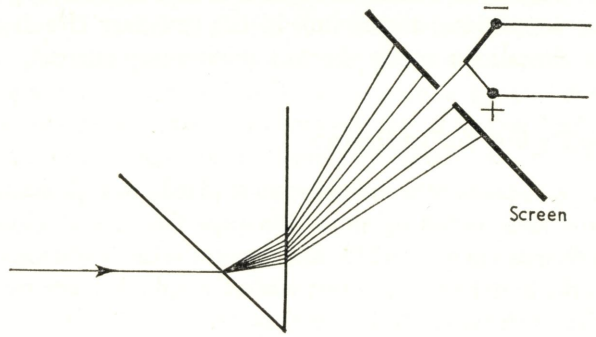


Fig. 3.2

rays may also be investigated by means of a thermocouple and a mirror galvanometer: the greatest effect is obtained with yellow and the least with ultra-violet. This shows that the effect depends not on the amount of incident radiation but on the frequency.

Deflection of cathode rays

Special tubes are available from educational supply firms for demonstrating the deflection of cathode rays, in which the rays are made visible, e.g. Plücker's Maltese Cross tube, and tubes with perforated anodes, or anodes placed out of a direct line: these have a suitable vacuum, about 0·01 mm Hg; Braun tubes.

Expt. 31. The deflection of the cathode rays in a magnetic field shows that they behave as though a positive current were flowing towards the cathode (Fleming's Left Hand Rule).

Expt. 32. The deflection by an electric field is shown by means of a cathode ray tube with capacitor plates sealed into it, e.g. Braun tubes in cathode ray oscillographs.

Electric effect with lamp bulb

Expt. 33. The upper half of an electric lamp bulb is covered with metal foil: this foil is connected to one terminal of a capacitor of about 5 μF, the other terminal being earthed. The capacitor has a sensitive ammeter and a switch in parallel with it. The lamp is kept alight for some time: the switch in the ammeter circuit is then suddenly closed: the meter shows a momentary current.

Kirchhoff's law for radiation

Expt. 34. A piece of wood charcoal is placed in a glass tube, and the open end is sealed up in a blow-pipe flame. The closed end with the charcoal is now held in the flame: the black charcoal shows that it is the better absorber, but when the tube is taken out of the flame, the charcoal is the better emitter.

The same effect may be shown by means of a glass rod with a

piece of black glass sealed into one end (Bindseil, PRAXIS, 1955/9, p. 242).

Black bodies

Expt. 35. A nearly perfect black body may be made by boring a hole of about 0·5 cm diameter in one of the smaller sides of a cigar box, which has both inside and outside coated with black paper. The side with the hole is now illuminated; the hole always looks darker than the side around it.

Stefan-Boltzmann law

Expt. 36 (fig. 3.3). A small blackened copper disk has soldered to it one junction of a eureka-copper thermocouple. The other

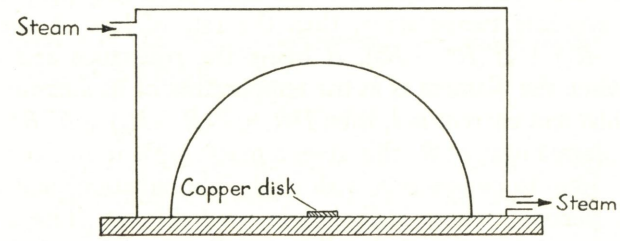


Fig. 3.3

junction is kept in melting ice in a thermos flask. The thermocouple is connected to a suitable galvanometer, through a resistance if necessary. The disk is placed flat on a horizontal heat-insulating surface. A hemisphere of sheet copper (conveniently half of a large copper sphere from a ballcock of a water cistern) is soldered with its concave surface downwards so that it forms the underside of a metal box which can be heated by passing steam through it. The inner surface of this hemisphere is blackened.

The box is first allowed to become thoroughly hot, and is then placed quickly over the copper disk so that the disk is at the centre of the previously open side of the hemisphere; the disk is then equidistant from all parts of the hemisphere. The rate of rise of temperature of the disk is then found by observing

the galvanometer deflections at intervals of about ten seconds. From the absolute temperatures of the steam and of the disk, the area of the disk, the mass and specific heat of the disk, and the rate of rise of temperature, Stefan's constant may then be calculated.

The thermocouple and galvanometer must previously have been calibrated at known temperatures (*Philosophical Magazine*, series 6, 1905, p. 270).

Expt. 37. The source of heat is the filament of a 6V car headlamp bulb. The energy loss from this is chiefly by conduction and by radiation. If T is the absolute filament temperature, and T_0 the temperature of the surroundings, then the conduction loss and the radiation loss are respectively $A(T - T_0)$ and $B(T^n - T_0^n)$, where A and B are constants and n the index of the radiation law. If it is assumed for tungsten that the resistance is directly proportional to the absolute temperature, then the rate of loss of energy is $A'(R - R_0) + B'(R^n - R_0^n)$, R being the resistance and R_0 its value when the filament is at the temperature of its surroundings. If the filament current is I, then $I^2R = A'(R - R_0) + B'(R^n - R_0^n)$. I^2R is plotted against R; this gives a graph with an initial straight portion (due to conduction with negligible radiation) and a final curved portion, where radiation is predominant. The straight portion is produced, and the difference between it and the final curve gives the value of the radiation term $B'(R^n - R_0^n)$. If now the logarithms of several values of $B'(R^n - R_0^n)$ are plotted against corresponding values of R, the slope of the graph gives n.

The resistance determinations may be done by (i) ammeter and voltmeter, (ii) Wheatstone's bridge, (iii) potentiometer. The last method is the best; the potentials across the lamp and across a fixed known resistance in series with it are found (F. G. Mee, SSR, 1930/46, p. 157, and *Science Masters' Book*, Part 1, Series 1, p. 56).

Expt. 38. The Stefan-Boltzmann law may also be verified by means of a cooling curve; any liquid will do for this, but the best results are obtained with mercury, since with mercury there are no losses through vaporization and so on. Inaccuracies due to

varying temperatures in different parts of the liquid are avoided, and also the specific heat is so low that the whole experiment may be performed in an hour. Further, the initial temperature may be as high as 300° C if a suitable thermometer is available.[1] A round-bottomed flask of about 100 cm³ capacity is used as container. As heat is being given out during cooling, one may either measure the time taken for the temperature to drop through intervals of 5° or 10°, or note the temperature at equal intervals of time. By means of these temperatures, the quantity Q of heat given out is calculated from Q = mass × sp. heat × temp. fall. These values are plotted on a graph with Q as ordinates and times as abscissae; from the curve thus obtained the gradient at a series of points is calculated, the calculation being like that of a velocity from a displacement-time curve, so

$$\text{slope of graph} = \frac{dQ}{dt}.$$

According to the Stefan-Boltzmann law, the quantity of heat radiated Q_a is given by:

$$Q_a = C_a T_a^4 . t$$

where T_a is the absolute temperature of the radiating body.

In the same time, t, however, the radiating body received heat Q_e radiated back to it by its surroundings, so

$$Q_e = C_e T_e^4 . t$$

where T_e is the room temperature.

Since the constants C_a and C_e for emission and absorption are the same, we may write $C_a = C_e = C$. Hence the resultant heat radiated, Q, is given by

$$Q = Q_a - Q_e = C(T_a^4 - T_e^4)t$$

By differentiation $\dfrac{dQ}{dt} = C(T_a^4 - T_e^4)$

and hence $\quad \text{slope} = C(T_a^4 - T_e^4)$

or $\quad \dfrac{T_a^4 - T_e^4}{\text{slope}} = \dfrac{1}{C} = c$

(Schlee, PRAXIS, 1954/2, p. 39)

[1] Above 300° C there is a danger of the mercury vaporizing.

If more time can be devoted to the Stefan-Boltzmann law, the method given by Herr Klein in MNU, 1951/52, p. 258 and 1952/53, p. 143 may well be used. The first part of the experiment is very like that of Herr Schlee; it requires, however, not only the determination of energy radiated, but a second experiment in which part of the radiated energy is collected; from this the total energy radiated is determined. The results of the two experiments are, however, not difficult to calculate.

Wien's Displacement law: $\lambda_{max} . T$ = constant

Expt. 39. A diffraction grating and a lamp bulb with a tungsten filament are used; the temperature of the filament is found as in the experiment on the Stefan-Boltzmann law. The highest possible voltage is used so as to give a bright spectrum: the distribution of the energy in this spectrum is then determined by means of a thermocouple and a sensitive galvanometer (a mirror galvanometer). To do this the thermocouple is moved sideways along a galvanometer scale which is placed in the spectrum about 30 cm behind the grating and perpendicular to the radiation. The voltage applied to the filament is then lowered step by step, until the temperature of the filament has fallen to about 500° C; the distribution of the energy is determined for each step. The values obtained are plotted on a graph as ordinates against the position of the thermocouple on the galvanometer scale. The results show that when the temperature is raised the point of maximum energy moves towards the shorter wavelength. In each case the maximum occurs always in the infra-red. Only with sunlight does the maximum begin to come within the visible spectrum (λ_{max} = 0·5 micron). O. Lummer later determined the constant in the Wien displacement law as 0·00288, so

$$\lambda_{max} . T_{abs} = 0{\cdot}00288$$

From this the temperature of the sun's surface may be determined:

$$T_{abs} = \frac{0{\cdot}00288}{0{\cdot}5 \times 10^{-6}} = 5760^{\circ}\ \mathrm{K}$$

Since a considerable part of the sun's energy is absorbed by the

gaseous outer layer of the sun, and by the earth's atmosphere, the real temperature of the sun must be higher than this. If this is known, then from the same equation it is also possible to calculate the wavelength of the radiation.

4

Determination of the constants *h, e, c*

(Planck's constant, charge on electron, velocity of light.)

Estimation of *h* to lower limit

Expt. 40 (fig. 4.1). A neon lamp, or two neon lamps in series (Osram 77·1225/e 33), are illuminated by light of various known

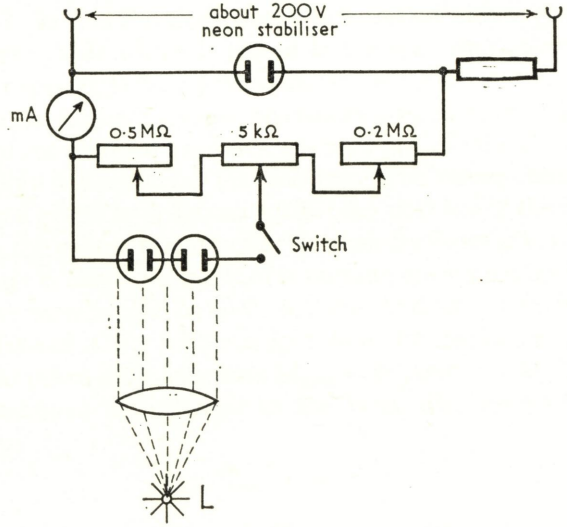


Fig. 4.1

wavelengths in turn by means of a mercury lamp and filters; the lowering of the striking voltage for the lamps is thereby found. In order to do this, the supply voltage to the neon lamps must be well stabilized. Since the lowering of the voltage is only of the order of

ten volts, the voltage near that necessary for striking the lamps must be capable of accurate measurement. This is done by means of a suitably arranged potentiometer (see diagram).

Under the influence of radiation of frequency ν the electrons emitted from the surface have an energy $h\nu - A = \Delta U.e$ given to them, where A is the work function, ΔU the observed lowering of the striking voltage, and $e = 1{\cdot}6 \times 10^{-12}$ erg.

In order to eliminate the uncertainty of the exact value of A, the experiment is done twice with frequencies ν_1 and ν_2; hence

$$h\nu_1 - A = \Delta U_1.e$$
$$h\nu_2 - A = \Delta U_2.e$$
$$\therefore h(\nu_1 - \nu_2) = (\Delta U_1 - \Delta U_2)e \text{ and so } h = \frac{(\Delta U_1 - \Delta U_2)}{(\nu_1 - \nu_2)}e$$

This procedure gives however a value of h somewhat too small, since both electrodes are irradiated. Free electrons are liberated from the anode by the impact of photons: these produce a small reverse field which causes the observed value of ΔU to be too small (Schröder, PRAXIS, 1955/1, p. 1, see also the *Science Masters' Book*, Series 1, Part 1, p. 217).

Estimation of *h* to upper limit

Expt. 41. A spectrum tube filled with hydrogen, and with its electrodes D cm apart, is set in action with the least possible stabilized voltage U—about 500 volts. This gives a striated discharge. The distance d between the striae is measured. The spectral distribution of the light shows that four visible hydrogen lines are present. A light-quantum of frequency ν has energy $h\nu$. This

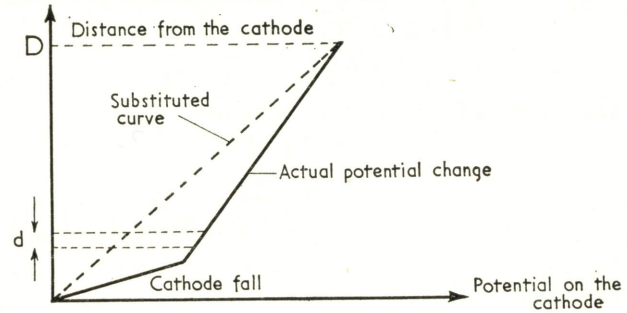


Fig. 4.2

amount of energy must be that gained by an electron in its passage from one striation to the next if the striated discharge is to be maintained. This is brought about by the voltage ΔU. To determine ΔU, the voltage drop across the discharge tube must be found. A calculation of ΔU by means of a single straight line on the graph (fig. 4.2) leads to a high value of ΔU.

$$\Delta U = U.\frac{d}{D}$$

The increase in energy between two striations is $\Delta U.e$, and this energy is expended in exciting the atom.

$$h\nu < \Delta U.e$$

Hence
$$h < \Delta\frac{U.e}{\nu}$$

To reduce the error in this inequality, the shortest of the four wavelengths is used, H_δ for which $\nu_\delta = 0{\cdot}73 \times 10^{15}$ sec^{-1}. This estimate can be made better by consideration of the quantum energy content of the Balmer series, in which the line H_δ comes fourth.

For the Balmer series $h\nu = Rh\left(\frac{1}{2^2} - \frac{1}{m^2}\right)$, where $m > 2$.

Therefore
$$h\nu = Rh\left(\frac{1}{2^2} - \frac{1}{6^2}\right) = Rh.\frac{8}{36}$$

When the atom is brought from the lowest energy level (Lyman series) to this excited level, it gains energy given by:

$$h\nu = Rh\left(\frac{1}{1^2} - \frac{1}{6^2}\right) = Rh.\frac{35}{36}$$

The energy of the photon $h\nu$ then corresponds to the quantity

$$\frac{\Delta U.e}{\nu_\delta}.\frac{8}{36}\Big/\frac{35}{36} = \frac{\Delta U.e}{\nu_\delta}.\frac{8}{35}$$

From which comes the more correct value

$$h < \frac{\Delta U.e}{\nu_\delta}.\frac{8}{35}$$

(Schröder, PRAXIS, 1955/1, p. 1)

Determination of h

Expt. 42 (fig. 4.3). An alkali photoelectric cell with a clear glass

bulb is illuminated by monochromatic light. The equation connecting the frequency ν of the incident light, Planck's constant h, the work function A of the electrons from the photocathode and $U.e$, the energy of the photoelectrons, is then $h\nu - A = U.e$.

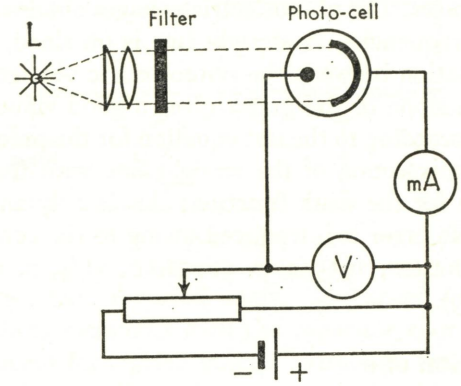


Fig. 4.3

A potential divider is connected to the cell, in order to find the voltage U for which the fastest electrons just do not reach the anode (Null method). Then we have:

$$h = \frac{A + U.e}{\nu} \text{ erg. sec. } (1\ e.V = 1{\cdot}6 \times 10^{-12} \text{ erg})$$

Since the work function A can be determined only roughly (for a caesium cell it is between 1·5 and 2 volts) the experiment is performed with two different frequencies ν_1 and ν_2; hence

$$h\nu_1 = e.U_1 + A$$
$$h\nu_2 = e.U_2 + A$$
$$\therefore h(\nu_1 - \nu_2) = e(U_1 - U_2)$$

and thus
$$h = \frac{e(U_1 - U_2)}{\nu_1 - \nu_2}$$

(Werner and Riehl, *Math. Ph. Ch. in der Schule*, 1952, p. 263)

Expt. 43. Instead of determining the photoelectric voltage by cancellation with a reverse voltage, as in the preceding experiment, it may also be determined directly with a sufficiently sensitive electrometer (a quadrant electrometer with one pair of quadrants connected to a negatively charged 'needle', as used by Franck). The

case and the other pair of quadrants are earthed; the wires are all screened, and the screens earthed. A mercury vapour lamp may be used as source of light, provided with filters to give four frequencies. The photocell must be well protected from stray light of other frequencies. The photoelectric voltages obtained are graphed against the frequencies. A straight line is obtained, which shows the linear relation between the photoelectric voltage and the frequency. The slope of the graph gives a good value for Planck's constant h, according to the last equation for the preceding experiment. The intersection of the straight line with the voltage axis gives a value for the work function; this is only an approximate value, since an error is introduced owing to the contact potential (Kraemer, PRAXIS, 1955/4, p. 92; MNU, VI/4, p. 168; PRAXIS, 1956/1, p. 19).

Determination of e

Expt. 44. Millikan's method: the theory may be found in physics textbooks.

$$ne = 18\pi\eta\sqrt{\frac{\eta}{2\rho g}}\cdot 300\frac{d}{U}\sqrt{V_0}(V_1 - V_0)$$

where d = distance between capacitor plates

U = voltage

V_0 = velocity without field

V_1 = velocity with field

A kind of smoke-chamber is used, like that described by Schimank in 'A demonstration of the Brownian motion'. In this chamber is a small capacitor with its plates about 5 mm apart: tobacco smoke is blown in. Water vapour will have condensed on the smoke particles in the mouth; some particles will also have gained a positive charge and some a negative one. The particles are observed through a microscope with magnification about 150 and having a scale in the eyepiece. The illumination should be from a projection lamp and at about 45° to the line of sight. The light is brought to a focus between the plates of the capacitor by means of a lens. As soon as the turbulence in the chamber has died down, the particles all begin to fall; the miscroscope will make them appear to rise. By means of a voltage divider, a voltage is now applied to the

capacitor plates, the upper one being positive (fig. 4.4). The actual voltage is determined by the size of the particles. The negatively charged particles now begin to move upwards. The capacitor is

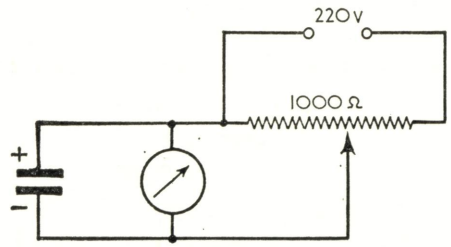


Fig. 4.4

then short circuited; they fall again. The speed of fall of one chosen particle is measured with the capacitor shorted, and also its speed of ascent for a given voltage. Although the particles will probably exhibit some Brownian motion, it should be possible to obtain measurements with several of them, and to find an average value of e from the equation (Dössel, MNU, III, 1950/51, Vol. 2, p. 105).

Expt. 45. Brodda and Stocker have given descriptions of home-made pieces of apparatus for performing Millikan's experiment with oildrops. These do not greatly differ from that due to Nokes (*Demonstrations in Modern Physics*, pp. 67–80—Heinemann) and that shown by Llowarch at courses in Great Britain (Brodda, MNU, VIII, 1955/56, Vol. 10, p. 466, and Stocker, PRAXIS, 1952/6, p. 153).

Determination of $\frac{e}{m}$

Expt. 46. A cylindrical former, wound with enamel-insulated copper wire of about 0·5 mm diameter, is placed round a cathode ray tube so that their axes coincide. If the length of the former is at least four times its diameter, the field in the middle of it is constant. If the electrons move along the axis common to the tube and the coil, they are not deflected by the application of the magnetic field. If however a voltage U is applied to the plates of a capacitor in the tube, the electrons move sideways with velocity v_u in a

circular path, so that they describe a helix in the tube. The radius of the circular path is given by

$$r = \frac{m}{e} \cdot \frac{v_u}{\mu_0 . H}$$

To make one complete turn of the helix, the electrons take a time given by

$$T = \frac{2\pi r}{v_u} = \frac{2\pi m}{e\mu_0 H}$$

which does not depend on v.

The current in the coil is adjusted so that the value of H is such that the electrons in traversing the distance p between the capacitor plates and the fluorescent screen do describe one turn of the helix. Then

$$T = \frac{p}{v}; \quad v = \sqrt{2\frac{e}{m}U_a}; \quad \frac{e}{m} = \frac{8\pi^2 U_a l^2}{\mu_0{}^2 I^2 n^2 p^2}$$

where U_a = anode voltage
n = number of turns in coil
l = length of coil
I = current in coil

The deflecting voltage U is conveniently an alternating one: H is then adjusted so that the line on the screen contracts to a point (independent of v) (Gente, PRAXIS, 1955/1, p. 9).

Expt. 47 (experiment with a Wehnelt tube). A heated piece of foil, made of a dense metal and with a spot of BaO, gives a sharp and narrow beam of cathode rays when a voltage U_a is applied. The tube is placed between two coils carrying a current; this current is adjusted until the magnetic field is large enough to bend the beam into a complete circle then

$$\frac{e}{m} = \frac{2U_a}{\mu_0{}^2 H^2 r^2}$$

(Ristau, MNU, 1950, vol. 5, p. 229)

Similar experiments with electron beam tubes as supplied by firms of school apparatus makers are described by Seus and Geier. For the determination of $\mu_0 H$ see Kahra, PRAXIS, 1955/4, p. 101.

Expt. 48. The disadvantage of the fact that the field due to the coils in Expt. 46 is not completely homogeneous may be overcome if the earth's magnetic field is made to produce the deflexion of the cathode rays. It is very weak, but the whole beam lies in the field. Expt. 49 describes how the earth's field may be determined. A Braun tube, without its metal shield, is placed so that the electron beam is perpendicular to the earth's magnetic field. The tube is then turned through 180° about a vertical axis. The spot of light on the fluorescent screen is deflected vertically through a distance $2x$. The anode voltage U, which should be as small as possible, is measured with an electrostatic voltmeter. Then

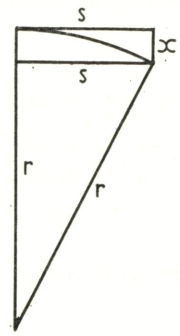


Fig. 4.5

$$\frac{e}{m} = \frac{2U}{\mu_0{}^2 . H_e{}^2 . r^2}$$

and

$$r = \frac{s^2 + x^2}{2x}$$

(Vollmer, MNU, VIII, 1954/55, vol. 3, p. 129)

Determination of the earth's magnetic field

Expt. 49 (fig. 4.6). A freely swinging compass needle is placed in a horizontal solenoid about 20 cm long, 5 cm in diameter and

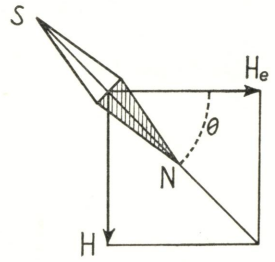


Fig. 4.6

having 100 turns. The needle settles down so that when no current is flowing, it is parallel to the earth's field. The solenoid is now turned so that its axis is perpendicular to the direction of the

needle. The current is then switched on, and is adjusted until the needle shows a deflexion of 45°. When this is so the field due to the coil equals the earth's horizontal component H_e.

So $$H_e = \frac{I.n}{l}$$

where I is the current
n „ „ number of turns
l „ „ length of the solenoid

The total intensity H of the earth's field may then be calculated from the equation $H = \frac{H_e}{\cos\theta}$, where θ is the angle of dip.

Determination of the velocity of light: Michelson's method

Expt. 50 (fig. 4.7). An image of an illuminated slit is formed on a plane mirror by means of a convex lens and of a mirror which can

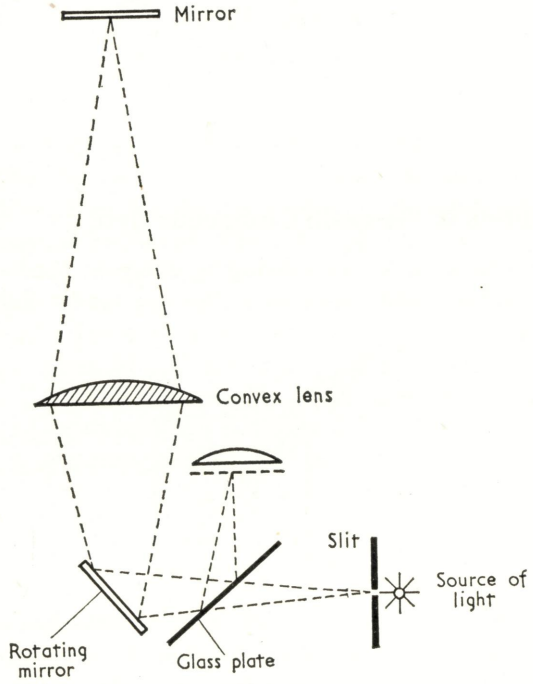


Fig. 4.7

be rotated. The light is reflected back again so that an image of the slit is formed at the slit itself. This image is observed by means of a glass plate arranged at 45°. When the mirror is rapidly rotated, the returning rays find it slightly moved and are thereby displaced with regard to the slit. The velocity of light can then be calculated by measurements of this displacement and of the speed of rotation of the mirror. Suitable apparatus is supplied by Leybold—Scientific Teaching Apparatus Ltd, 27–37 Broadwick Street, London, W.1 (Lindberg, PRAXIS, 1955/4, p. 85).

Velocity of electromagnetic waves

Expt. 51. A determination of the velocity of electromagnetic waves by means of the equation $c = \nu\lambda$ requires independent measurements of the frequency of the waves and of their length. The wavelength may be found by means of Lecher wires in the usual way. The frequency may be determined as follows:

A coupling coil is made of about the same dimensions as the oscillating coil, and a torch bulb is soldered on to act as a resonance indicator: the coil is connected to a variable trimmer capacitor C of about 25 pF (fig. 4.8). The coil is brought into resonance by adjusting the capacitor to a setting C_1. A fixed capacitor of exactly 10 pF is then put in parallel with C_1 and C is adjusted to a setting C_1' so as to bring the circuit again into resonance. This corresponds to a difference $C_1' - C_1 \triangleq 10$ pF. Hence C_1 may be found. Now the variable capacitor is connected to a standard coil, of about 50 turns of copper wire of diameter 1 mm, the self-inductance of which is given by $L_H = 4\pi^2.10^{-9}\frac{n^2r^2}{l}$. If C is now adjusted to a value C_2 the circuit can again be brought to resonance. The calculation, as given in the reference, shows that

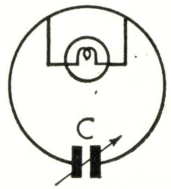


Fig. 4.8

$$c = \frac{\lambda}{2\pi\sqrt{L_H(C_2 - C_1)}}$$

(Athen, PRAXIS, 1952/11, p. 321)

5
Fluorescence and photoelectricity

Stokes's law of fluorescence

Light is absorbed by many substances: these transform the light energy into heat: dark and rough surfaces do this more than bright and smooth ones. Other substances transform the incident light into light of longer wavelength.

Expt. 52 (fig. 5.1). If a beam of light is passed through a trough of alkaline solution of fluorescein, the beam shows a green fluores-

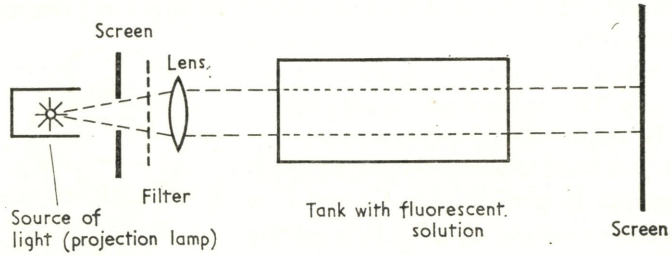


Fig. 5.1

cence, but the light which has passed through the solution and then falls on a screen appears yellow. If coloured filters are placed in the path of the light to the trough, then the solution fluoresces only if the incident light is of higher frequency than that of the fluorescent light. Hence red light produces no fluorescence.

Excitation of atoms by resonance

Fluorescence of sodium vapour

Expt. 53. A distilling flask of volume about 500 cm^3 is filled with carbon dioxide, and about $\frac{1}{2}$ cm^3 of sodium is put in it after

being carefully freed from paraffin and having had any surface oxidation removed. The wide tube is then sealed up in a blowpipe flame. The narrow side tube is then connected to a vacuum pump; a good vacuum is obtained, and the side tube is then sealed too. The remaining carbon dioxide is of no consequence, since when the flask is used it will be absorbed by the sodium. The flask is then heated underneath with a brush flame until the sodium melts. Some of it vaporizes and then condenses again on the colder parts of the flask. This condensed sodium is driven into the neck of the flask by heating the whole of the rest of the flask. With this flask the excitation of sodium can be shown repeatedly. A convergent beam of light from a sodium lamp is sent through the flask by means of a lens: the flask is gently heated with a bunsen flame so as to produce a steadily increasing pressure of sodium vapour. At a certain pressure, first the whole flask lights up, and then as the vapour pressure increases the fluorescent beam gets shorter and shorter until finally it is apparent only just where the light enters the flask (Keutel, PRAXIS, 1954/5, p. 154).

Photoelectric effect

Expt. 54. Two equal zinc plates each about 50 cm^2 in area are placed in very slightly acidulated water, and are connected directly to a sensitive galvanometer in a darkened room. A small current flows, since the surfaces of the plates are bound to be in slightly different condition. The anode is now illuminated with light either from a mercury lamp or from a burning piece of magnesium ribbon: the galvanometer deflection becomes slightly less; but if the cathode is illuminated, the current becomes considerably greater.

Expt. 55 (Hallwachs's original experiment of 1887). The light from an arc lamp is allowed to pass through a quartz plate on to a plate of zinc just previously cleaned with emery cloth; the plate is connected to a negatively charged gold-leaf electroscope. Illumination with ultra-violet rays causes electrons to be ejected from the zinc plate: these go off to the air, and the surplus electrons from the electroscope move towards the zinc, so that the electroscope leaves converge. If however the electroscope is positively charged, no effect is produced.

Expt. 56. If it is not desired to show the experiment exactly as Hallwachs did it, then an ultra-violet lamp may be used, or Lenard's version may be shown. The plate and point of an induction coil are adjusted to be so far apart that hardly any sparks pass. When the negative electrode is illuminated with u.v. rays, sparks pass freely.

Expt. 57 (with X-rays). If X-rays are allowed to fall on the zinc plate in Expt. 55, the electroscope leaves quickly come to a given value which thereafter does not change. This is because there is not only a photoelectric effect due to the X-rays, but also an ionizing action on the air in front of the zinc plate which causes the positive charge produced on the plate to be partly cancelled out. If the ions produced by the X-rays are now removed by a stream of air, the electroscope potential will be about doubled. If the electroscope has in front of it a thick glass plate, the X-rays will then produce a divergence smaller than the previously determined one: this will also become constant. There is then a balance between the charge produced by the photoelectric effect and that lost by the ions produced in the air.

Photoelectric effect with a neon lamp

When light falls on the surface of a metal, the surface emits electrons whose velocity depends only on the wavelength of the light and not on its intensity.

Expt. 58. A neon lamp is connected by means of a potential divider to the a.c. mains, and is illuminated by u.v. rays from an arc lamp, etc. The voltage is adjusted so that the neon lamp only just lights up: if now the illumination is cut off by a screen, the lamp will go out. When the screen is removed the neon lamp lights up again. The dependence of the effect on the wavelength of the incident radiation may be shown by putting coloured filters in the path of the light. With red, yellow, or green light, the neon lamp will not light up.

Expt. 59 ($E = hv$ qualitatively). An Anson-Pearson ticking circuit is used, as shown in fig. 5.2: this is best with small neon

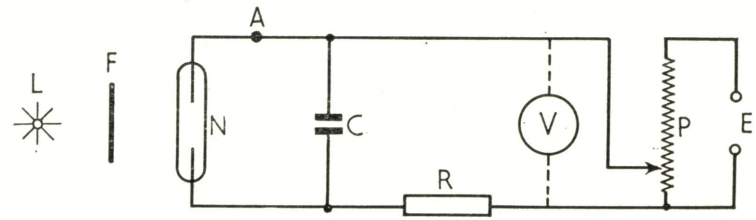


Fig. 5.2

L = source of light (projection lamp, u.v. lamp, Röntgen tube)
F = filter (red or blue)
N = neon lamp
C = capacitor (2 μF)
R = resistance (1 MΩ)
P = potential divider
E = d.c. voltage, 60 to 130 V
V = voltmeter, removed before each reading

lamps, since big ones are not so sensitive. When the potential across the capacitor rises to the striking potential of the neon lamp, the capacitor discharges through the lamp, which gives a flash. The process, once started, repeats itself periodically (relaxation oscillations) and the flash frequency, or its reciprocal the 'light-time', may be determined by experiment or calculated from C, R, E, E_z and E_L (the potential at extinction). The change in T produced by a change in the supply voltage E (from 60 to 130 volts) is now determined and the values obtained are graphed (fig. 5.3). As E increases, the value of T falls, i.e. if E is approx. equal to E_z, T is a maximum. The curve (a) was obtained in complete darkness.

The striking voltage E_z of a neon lamp may also be reduced when the lamp is irradiated with light (or u.v. rays or X-rays), since the electrons absorb the energy of the light quanta. The previous experiment is now repeated with the neon lamp illuminated with white light from a projection lamp. The values of T, obtained when E is varied, are again graphed and give curve (b). The flash period T is reduced in white light by about a third or a half, so the frequency is increased. A red filter and then a blue one are now inserted in the path of the light, E is again varied, and the corresponding values of T noted: this gives two further curves (c) and (d) which lie between curve (a) obtained in darkness and

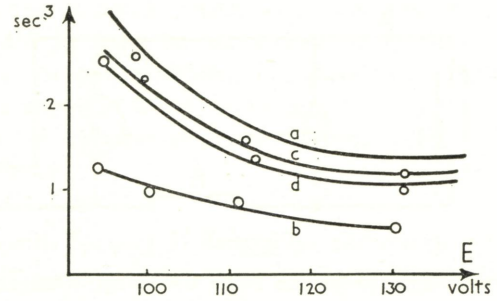


Fig. 5.3

curve (*b*) obtained in white light. The curve for red light lies only slightly below curve (*a*) for darkness since red light provides little energy, whereas curve (*d*) for blue light shows a decrease of about 30% in the flash-period *T*.

The photoelectric effect is thus demonstrated qualitatively by the decrease in the flash-period; it is also shown graphically. (For theory of this, see Athen, PRASCHU, 1951, pp. 175–83.)

Expt. 60. If a loudspeaker is included at point *A* in the circuit for Expt. 59, capacitor discharges which are difficult to see may instead be made audible (Seus, PRAXIS, 1956/4, p. 87).

Experiments with photoelectric cells

When the sensitive layer on the cathode is irradiated with light, so much energy is absorbed by it that electrons are ejected towards the anode. The number of electrons which pass over in this way is dependent on the intensity of the illumination and on the potential difference between the electrodes of the cell.

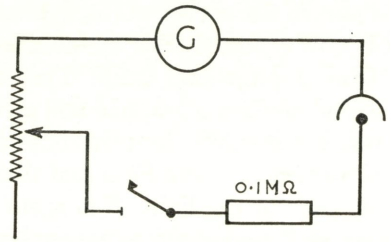


Fig. 5.4

Expt. 61. The distance of the source of light from the cell is doubled: the galvanometer shows that the current now has only a quarter of its previous value.

Expt. 62. Various coloured glasses (red, yellow, green, blue) are put between the source of light and the cell. Different deflections of the galvanometer are obtained: these vary with the sensitive material on the cathode (CsSb coating is best for u.v. rays; CsO_2 coating for infra-red and so on).[1]

Expt. 63. When the sensitivity of the photocell has been roughly determined by means of coloured glasses, the broadest possible spectrum given by an arc lamp and a prism may then be used. The photocell, placed behind the space between two screens, as in Expt. 29, is then traversed along the spectrum so as to obtain a sensitivity graph. The direct light from the arc lamp must be carefully shielded off. This will show, according to the sensitive layer of the cell, values both beyond the visible red, i.e. extension into the infra-red, and also beyond the visible violet, i.e. extension into X-rays: these may even be the highest values (Möller, MNU, 111/4, p. 241).

Interaction between light, electricity, and magnetism

(*a*) *The Kerr effect*

This is a demonstration of the fact that some substances, under the influence of an electric field, become doubly refracting.

Expt. 64. A Kerr cell, filled with very pure air-free nitrobenzene, is set up as shown in fig. 5.5. When a voltage is applied to the

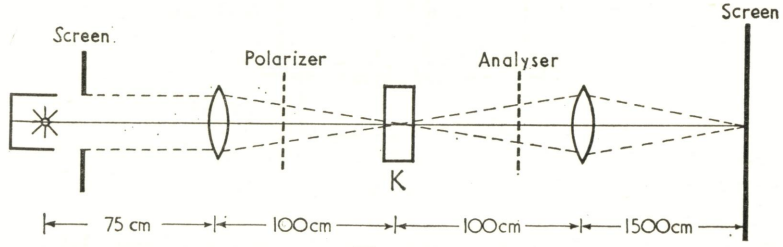


Fig. 5.5

[1] Since coloured glasses give different absorptions, the values obtained are only qualitative ones.

cell, the nitrobenzene becomes doubly refracting. If polarizer and analyser are arranged so that the rays coming through the cell, with no applied voltage, are extinguished, then when the voltage is applied some light will come through, and the intensity of this light is directly proportional to the voltage.

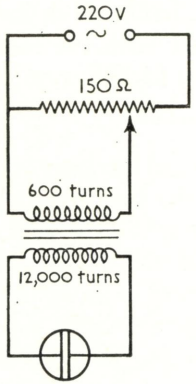


Fig. 5.6

Since commercial nitrobenzene is generally impure, and since dissociation owing to these impurities speedily destroys a direct voltage electric field, it is possible to observe the effect for only a short time. It is therefore better to work with high voltage alternating current, obtained, as shown in fig. 5.6, by means of a potential divider and a transformer. In this way the voltage applied to the Kerr cell may be set at any value between 0 and 5000 volts (Wölz, PRAXIS, 1954/7, p. 226).

(*b*) *The Faraday effect*

This produces a rotation of the plane of polarization of the light by means of a magnetic field.

Expt. 65 (fig. 5.7). Instead of the Kerr cell used in the preceding experiment, an electromagnet, with holes drilled through its pole

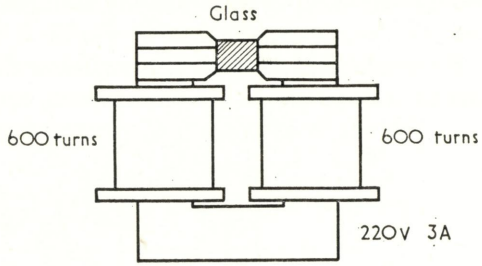


Fig. 5.7

pieces, is used. A plane parallel slab of flint glass (lead glass) is placed between the pole pieces. When the current is turned on, a rotation of the plane of polarization of the light passing through

the pole pieces is produced: this may be made more obvious by reversing the current. Here, too, the amount of light coming through is proportional to the strength of the field.

The electromagnet is energized with direct current. If the reversal of this is omitted, the whole experiment may be done in a very short time, so that a current of about 6 amps may be used in order to obtain a strong magnetic field.

Expt. 66. The Faraday effect for a liquid may be shown by means of a graduated cylinder, inside the bottom of which is placed a plane mirror. The remainder of the apparatus is shown in fig. 5.8. This arrangement has the advantage that as the light passes

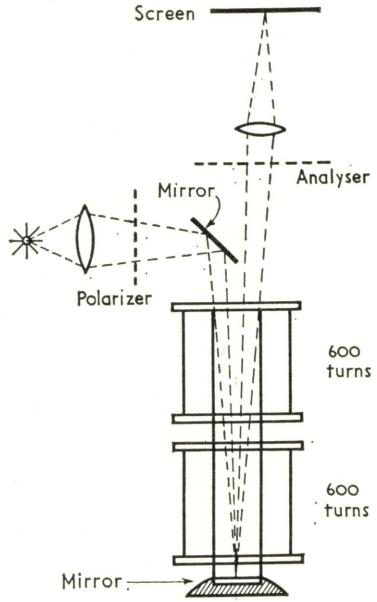


Fig. 5.8

twice through the column of liquid, a larger rotation is produced. At the same time, one can demonstrate the fact that the rotation depends directly on the length of the liquid; and different liquids may be used, e.g. carbon disulphide, creosote, nitrobenzene, and solutions of iron chloride and other salts (Schröder, PRAXIS, 1954/10, p. 342).

(*c*) *The Zeeman effect*

This is the splitting of spectral lines in a magnetic field. It is hardly possible to demonstrate the real effect with school apparatus: but it is possible to show the inverse effect which arises when a beam of sodium light is sent through a sodium flame burning between the two drilled-out pole pieces (see fig. 5.9). When the

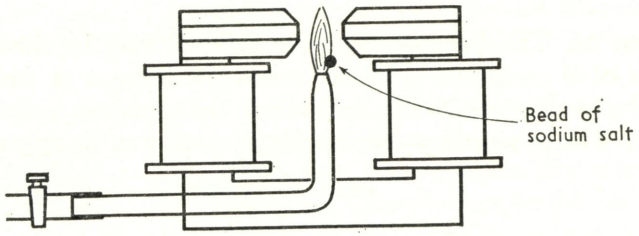


Fig. 5.9

magnetic field is put on, the orbital energies in the sodium atoms are altered, and this causes an alteration in the frequencies of the spectrum emitted. From this follows a decrease in the absorption, and hence a brightening of the image of the flame.

Expt. 67 (fig. 5.10). Light from a sodium lamp or sodium arc light passes through a hole in a screen and is sharply focussed

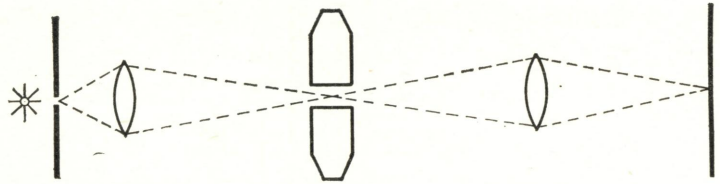


Fig. 5.10

between the pole pieces: this in turn is sharply focussed on a second screen. Then a flame is placed between the pole pieces and is coloured with a sodium salt (on magnesia stick or platinum wire). The spot of light on the screen, previously bright, then becomes dark. If the magnet is now energized, the spot becomes perceptibly brighter. It is essential in this experiment to have a flame of the right height, and to feed the sodium salt into the side of the flame further from the screen.

Expt. 68. If these experiments are to be shown more nearly in the way generally used for the Zeeman effect, then an arrangement may be set up like that which was used for the Faraday effect. Light from an arc lamp with sodium impregnated carbons is concentrated on a screen with an opening O; the rays from this opening are made parallel by a lens L_1. Part of this parallel light goes through the polarizer P, through the holes in the pole pieces, through the analyser A, and is then focussed on the slit Sp of a spectroscope by a lens L_2. The space between the pole pieces must lie inside the focus of the lens L_2. A bunsen flame coloured by a sodium salt is then placed between the pole pieces; the sodium lines can then again be seen in the spectroscope, although the polarizer and analyser were arranged to give extinction of the light. The magnetic field is now put on: bright bands of light appear on either side of the sodium lines which can be attributed only to the variation in frequency previously discussed. (Hence no splitting of the spectral lines and thus no normal Zeeman effect.)

Expt. 69 (fig. 5.11). Two sodium lamps N_1 and N_2 are placed about 50 cm apart, so that an image of lamp N_1 is formed at lamp

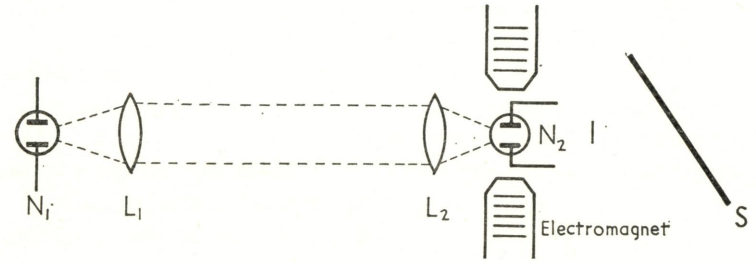


Fig. 5.11

N_2 by means of lenses L_1 and L_2 each of 100 mm focal length. N_2 stands between the pole pieces of an electromagnet. The intensity of the light transmitted may be seen on the screen S. N_1 and N_2 are switched on and both emit the characteristic yellow sodium light.

If N_2 is switched off, the sodium vapour in it still fluoresces, owing to resonance, as long as the light from N_1 falls on it. The screen is then dark. After a few minutes, the sodium vapour in N_2 has cooled down so much that the fluorescent light disappears,

and the screen now shows the light transmitted through N_2 from N_1.

If the magnetic field is put on whilst the resonance fluorescence is still apparent, the fluorescence becomes weaker, but the screen S brighter. The magnetic field causes a change in the frequencies of the two sodium lines of N_2 so that they no longer agree with the frequencies of the sodium lines emitted by N_1. Absorption is thus no longer possible, and hence also there is no fluorescence (Schmillen, PRAXIS, 1956/5, p. 119).

6
Proof of the atomic structure of matter

Law of constant proportions

Expt. 70. Fresh lead filings are mixed with excess of sulphur in the proportions 1 : 1·1; 1 : 1·5; 1 : 2 and the mixtures are heated in closed crucibles. The lead always combines with the sulphur so that there are 32 parts by weight of sulphur to 207 of lead. The excess sulphur evaporates and burns outside the crucible.

Law of multiple proportions

Expt. 71. If lead tetroxide is heated in an electric oven for about 15 minutes at 500° C, the lead tetroxide changes into a mixture of lead peroxide and tetroxide (red lead). After the mixture has cooled, the loss in weight may be determined.

The same container, with the red lead, is then heated to about 800° C, which brings about a new change to lead peroxide; the loss in weight is now about one half that caused by the first heating.

Further reduction, by means of hydrogen, may be brought about by heating strongly to red heat.

When lead peroxide is heated strongly above 800° C, part of it combines with the glaze of the crucible, so is lost for the further reduction with hydrogen. It is therefore desirable for this part of the reaction to use some fresh oxide mixture such as was produced in the second part of the experiment.

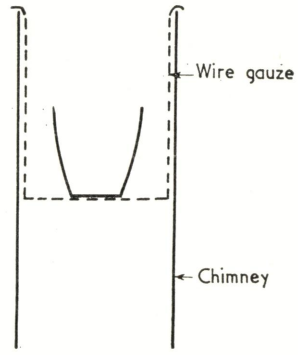


Fig. 6.1

Instead of determining the loss of weight, the oxygen content may be found volumetrically by means of gas measuring vessels. Preliminary experiment will show that the temperature of 500° C may be obtained sufficiently closely by means of a bunsen burner with a chimney (fig. 6.1). The bunsen flame should be about 10 cm high with the yellow cap just not perceptible. The temperature of the reaction is regulated by varying the distance of the flame from the bottom of the crucible.

Electrons in all substances

Expt. 72. A piece of foam plastic (or even soft india-rubber) is rubbed along the demonstration bench, and is brought to the electroscope so as to show the electric charge obtained. Then one 'scrapes electrons' from the blackboard, window-pane, and so on. If the plastic is rubbed over the hair, one can obtain as much as 2000 volts.

The Barkhausen effect

Expt. 73. About 8 metres of insulated copper wire, 1 mm in diameter, is wound round a glass tube some 5 cm long and 1 cm in diameter: it is fastened in place with wax (Keutel uses a transformer coil with 12 000 turns). A piece of soft iron wire 8 cm long and 0·2 mm thick is fixed by means of corks so as to lie along the axis of the tube. The coil is then connected by coaxial cable to the amplifier of a radio set (the pick-up terminals). A magnet is brought near the iron wire: the sound produced by the change in direction of magnetization of the domains is then audible. If a thicker wire is used, hissing and rustling is heard (Keutel, PRAXIS, 1954/7, p. 228 and PRAXIS, 1956/3, p. 72).

Expt. 74. Instead of the coil described above, the coils of an old high resistance headphone may be used. The difference between soft iron and steel becomes evident in this way: with soft iron, each time it is brought near to, or taken away from, the same pole of the magnet, there is a rustling sound like 'dash-dot'; but with steel, the first time it is brought near, there is merely a 'dash'. Further movement produces no sound. If the poles are reversed, there is again a 'dash'. To get a 'dash-dot' sound with steel, the

polarity must be continually reversed. If the steel wire is heated carefully, it acquires the magnetic properties of iron (Krumm, PRAXIS, 1956/3, p. 72).

Determination of Avogadro's number

Expt. 75. 0·1 g of olive oil[1] is dissolved in 100 cm³ of benzene and the number of drops in 1 cm³ of the solution is determined by means of a burette. Then a single drop is taken on the end of a glass rod; the benzene is allowed to evaporate, and the rod is dipped several times into a big vessel containing water, the surface of which has been thinly covered with lycopodium powder. The oil forms a layer of monomolecular thickness; the lycopodium powder retreats in front of it.

Calculation. One cm³ contains, say, 50 drops, so each drop has a volume of 0·02 cm³ and contains 0·000020 g of oil. If the oil has a density of 0·9 g/cm³, then a drop contains 0·000022 cm³ of oil. This forms a circle on the water, of about 16 cm diameter, so that the thickness d of the film, which is the thickness of the molecule, is given by volume = area of circle × thickness, so

$$d = \frac{0{\cdot}000022 \text{ cm}^3}{\pi \times 8^2 \text{ cm}^2} = 1{\cdot}2 \times 10^{-7} \text{ cm}.$$

The molecular volume may be calculated from the molecular weight and the density, i.e. $\frac{885}{0{\cdot}9}$, which is about 980. From this we get the number of molecules in one mole, $N = \frac{980}{d^3} = 6 \times 10^{23}$. The accepted value is $6{\cdot}03 \times 10^{23}$ (Seeger, MNU, III/3, p. 177).

Further calculations

(i) *Mean diameter of an atom.* An approximate value for the atomic diameter may be obtained from the thickness of the oil film. Since the average number of atoms in the molecule of olive oil is 167, the mean atomic volume

$$V = \frac{d^3}{167} \text{ cm}^3 = \frac{1{\cdot}75 \times 10^{-21}}{167} \text{ cm}^3 = 1 \times 10^{-28} \text{ cm}^3$$

[1] It is better to use oleic acid rather than olive oil, since its constitution and molecular weight are accurately known.

and hence $$2r = \sqrt[3]{\frac{6V}{\pi}}\ \text{cm} = 2{\cdot}7 \times 10^{-8}\ \text{cm}$$

(ii) *Atomic diameter of elements.* The atomic volume may be calculated by means of Avogadro's number N from

$$\text{atomic volume} = \frac{\text{volume of 1 mole}}{N \times \text{valency}}$$

$$\text{since volume of 1 mole} = \frac{\text{molecular weight}}{\text{density}}$$

E.g. for silver: atomic weight 107·88; density 10·5 g/cm³; hence volume of 1 mole = 10·3 cm³

and $$\text{atomic volume} = \frac{10{\cdot}3}{N}\ \text{cm}^3 = 1{\cdot}7 \times 10^{-23}\ \text{cm}^3$$

and hence $$2r = \sqrt[3]{\frac{6 \times \text{at. vol.}}{\pi}}\ \text{cm} = 3{\cdot}2 \times 10^{-8}\ \text{cm}$$

(iii) *Mass of the hydrogen atom.* Since 1 gram-atom of hydrogen has a mass of 1 g, then

$$m_H = \frac{1}{N}\,\text{g} = 1{\cdot}67 \times 10^{-24}\,\text{g}$$

(iv) *The elementary quantity of electric charge, e.*

From Faraday's number we obtain

$$e = \frac{96\,500\ \text{coulombs}}{N} = 1{\cdot}6 \times 10^{-19}\ \text{coulombs}$$

Conversely, N may be obtained if we know e and Faraday's number.

Expt. 76. A drop of olive oil is put on a glass plate, and the end of a steel wire about 0·3 mm in diameter is dipped into it. Some oil adheres to the wire; the volume of this may be estimated by means of a microscope with an eyepiece scale (Ristau, MNU, II, 5, p. 228).

Expt. 77. N may also be determined from the velocity of ions, v, and Stokes's law for the viscosity of fluids. $R = 6\pi\eta rv$, where η is the coefficient of viscosity for water, $8{\cdot}9 \times 10^{-3}$ g cm^{-1} sec^{-1}, r is the radius of the ions, and R the resisting force.

The motion is caused by the electric force $K = eE$, where E is

the applied field strength. Then $6\pi\eta rv = eE \times 10^7$, the values being measured in cm, g, sec, coulombs, and volts/cm. If U is the applied voltage and d the distance between the electrodes, then

$$E = \frac{U}{d}$$

and hence $$6\pi\eta rv = e\frac{U}{d}\,10^7$$

and hence $$\frac{e}{r} = \frac{6\pi\eta vd}{U} \times 10^{-7}$$

From this other values of the right order may be obtained. To determine v, Nernst's apparatus (Expt. 20) may be used, or alternatively Pohl's arrangement (Expt. 19) in which the distance s and the time t are measured.

From these

$$\frac{e}{r} = \frac{6\pi\eta ds}{Ut} \times 10^{-7}\varepsilon = B$$

where ε is a correction factor for the difference between the actual path of an ion and a straight line; a probable value for this is

$$\frac{1 + \frac{\pi}{2}}{2} = 1{\cdot}285$$

Then, from $\frac{e}{r}$ and Avogadro's number N,

$$\frac{Ne}{Nr} = \frac{F}{Nr} = B, \text{ where } F = 96\,500 \text{ coulombs}$$

Further, from the molecular weight M, and density ρ: and assuming that the substance is cubical, r is then given by

$$r = \frac{1}{2}\sqrt[3]{\frac{M}{2N\rho}}.$$

Each ion of this compound belongs to eight cubes, so each elementary cube consists of half an ion of different charges. Since one mole has N negative and N positive ions, there are therefore $2N$ such elementary cubes of side $a = 2r$. The volume V of the

elementary cube may then be calculated from $V = \frac{M}{\rho}$ by the equation

$$V_1 = \frac{V}{2N} = \frac{M}{2N\rho}$$

and hence the cube side

$$a = \sqrt[3]{V_1} = \sqrt[3]{\frac{M}{2N\rho}}$$

and the ionic radius

$$r = \frac{1}{2}\sqrt[3]{\frac{M}{2N\rho}}$$

Equating both values of r,

$$\frac{1}{2}\sqrt[3]{\frac{M}{2N\rho}} = \frac{F}{BN}$$

and hence

$$N = 4\sqrt[2]{\frac{\rho}{M}\left(\frac{F}{B}\right)^3}$$

(Athen, PRAXIS, 1952/5, p. 120)

Brownian motion

(*a*) *For liquids*

Expt. 78. A drop of water is put on a microscope slide, and a little watercolour paint is put into it by means of a brush. The experiment succeeds best with the thinnest possible drop and a very small quantity of paint. Several kinds of colour are suitable, but black or white pigments are best. Under the microscope, with magnification 500, first big particles are visible, and then in the deeper layers smaller ones, which move about in all directions: their motions are due to the impact of the water molecules of the suspension.

Instead of watercolours, or vermilion, the painter's colour titanium dioxide, suspended in some water, is particularly good (Rompp).

Expt. 79. A small quantity of aluminium powder (silverbronze) is stirred up with water in an electrolytic cell or in a beaker: when the water has come to rest, it is illuminated with parallel light. The random movement of the small particles may then be observed on the screen.

Expt. 80. A clock glass is illuminated from below by a projec-

tion lamp, the surface of the glass being sharply focussed on the ceiling (or, by means of a mirror at 45°, on the wall). A solution of sulphur in carbon disulphide is then placed in the clock glass. As evaporation proceeds, a number of crystals of sulphur begin to form, and quickly grow larger. However, as new ones are continually produced, there are always many different sizes in the solution; these show the characteristic Brownian motion (Reimers, PRAXIS, 1952/10, p. 300).

Expt. 81. The behaviour of particles of resin in water may also be seen by microprojection. The liquid quickly evaporates, due to the heating caused by the projection, so water must be added from time to time (Reimers, PRAXIS, 1955/9, p. 242).

(*b*) *For gases*

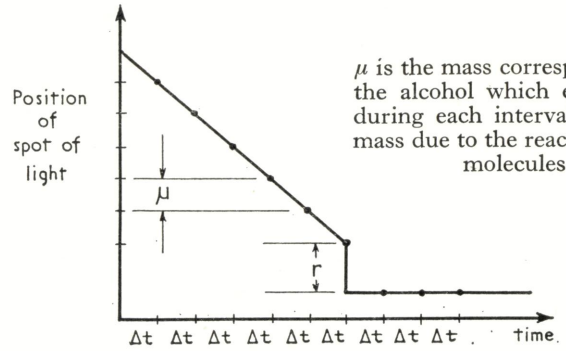
Expt. 82. This is best shown by means of a small transparent plastic box, which is filled with cigarette smoke or ammonium chloride fumes. The box is placed under the microscope and illuminated with a strongly convergent beam of light. After a short time the general turbulence subsides; then one can see, particularly at the point where the light is focussed, the motion of the particles of smoke; these are bumped hither and thither by the impact of the molecules of air. This may be shown with a much lower magnification than that used in Expt. 78.

Mean thermal velocity of molecules

Expt. 83. The mean thermal velocity of molecules may be determined from the mechanical reaction which the molecules of a liquid produce when they are vaporized. A small piece of mirror glass (15 × 10 × 1 mm) is fixed to the beam of a balance sensitive to 10 milligrams, so that a beam of light may be reflected from it on to a wall. On one scale pan a clock glass (8 cm diameter) is fixed by means of wax. A similar clock glass is hung upside down about 4–5 cm above the first one, by means of a hooked wire fixed to its back. The end of the pointer of the balance is immersed in an oil bath to damp out vibrations.

The lower clock glass is filled with methanol (or carbon tetrachloride or benzol): the upper one is put on top of it, and the whole

is counterbalanced. The 'lid' glass is then removed and hung up by means of the hooked wire. The position of the spot of light is then observed at equal intervals of time, say 15 to 30 seconds. After three or four readings the balance beam is lowered to its rest position, and at the end of the next interval of time, the glass is closed by means of the 'lid'. The balance is put into action again: the position of the spot of light now remains stationary. It will be found that the difference in position of the spot of light for the last two readings is greater than the difference between successive readings in the first part of the experiment. These differences, for equal intervals Δt, were constant. The positions of the spot of light are now plotted against time (fig. 6.2).



μ is the mass corresponding to the alcohol which evaporated during each interval. r is the mass due to the reaction of the molecules

Fig. 6.2

The velocity may then be calculated from:

$$v = 2g\frac{r}{\mu}.\Delta t, \text{ where } g = 981 \text{ cm/sec}^2$$

(Tamme, *Math. Ph. Ch. in der Schule*, 1952, p. 328)

7
Impact, spin, and interference of electrons

Ionization by impact of electrons (after Franck and Hertz)

Expt. 84. Franck and Hertz accelerated electrons in gases (first they used mercury vapour) and thus made observations of the energy of electrons. Physics textbooks of degree standard may be consulted for the theory of the effect. The periodical emission of slow electrons during excitation of spectral lines can be demonstrated qualitatively by arranging an electric discharge in an evacuated discharge tube. It can be shown quantitatively during excitation by electron impact of the Hg line 253·7 mμ that slow electrons

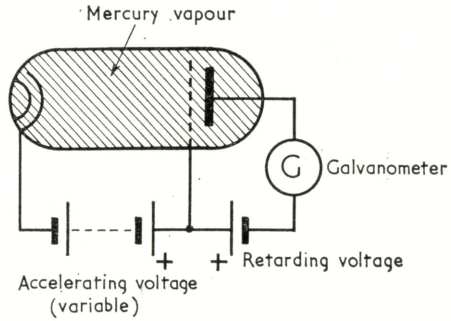


Fig. 7.1

are periodically produced. The slow electrons produced by this arrangement are unable to reach the anode owing to the reverse field. Franck and Hertz obtained as oscillograms the curves shown in Expt. 85, from which it may be seen that the excitation energy for the line 253·7 mμ is exactly 4·9 electron-volts.

Expt. 85. This experiment may be done with commercially

available mercury vapour filled triodes: these however may lead to the following errors:

(i) The number of electrons is much too great for the available mercury vapour, so that not all of the electrons are used to produce excitation and the ionization energy will be far from the 10·3 electron-volts for mercury. The first maximum at 4·9 electron-volts may be evident, but not very clearly.

(ii) Unsuitable arrangement of the electrodes may entirely falsify the effect.

(iii) Directly heated cathodes may cause errors due to the drop in potential.

When all these sources of error have been taken into account, the curves obtained by Franck and Hertz may be shown on a cathode ray oscillograph (Principle of obtaining characteristic lines).

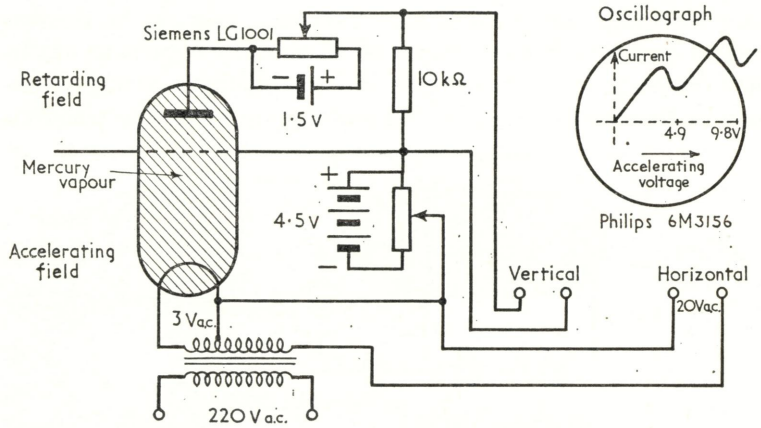


Fig. 7.2 The oscillograph must not have a common earth for the x plate and y plate; high gain is necessary

The experiment may be done with Siemens valve LG 1001 and Philips oscillograph GM 3156.

Electron impact with mercury valves

Gehrke and Seeliger report in *Verh. d. Deutsch Phys. Ges.*, vol. 14, pp. 335 and 1023 (1912) on 'Observations on emission of light

along a beam of cathode rays'. A narrow beam of cathode rays is produced in argon at low pressure by means of a cathode K, directed towards a wire gauze anode A, about 1 cm from it, inclined at an angle α to the vertical. A reverse field is produced by a wire gauze cathode K_1, parallel to the anode and about 3 cm from it (see fig. 7.3). The beam follows a parabolic path, so as to be

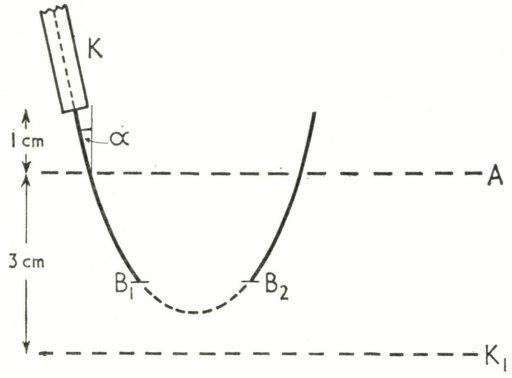


Fig. 7.3

turned away from the second cathode. The greater part of this parabola is visible as a glowing trace, because the cathode ray beam has sufficient acceleration, but the part B_1B_2 near the origin is not visible. The visibility of the two sides ends and begins suddenly at equal distances from the origin.

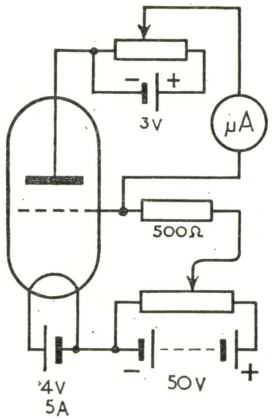


Fig. 7.4

Expt. 86 (fig. 7.4). For school demonstrations a thyratron or neon-filled valve is suitable. Valves of this kind are easily workable at room temperature and show the electrical effect of the appearance of maxima and minima visually by the sudden change in colour of the gas contained and spectroscopically by the appearance of new lines as the accelerating voltage is increased.

When this voltage is 15–20 volts the mercury vapour gives a greenish-blue light, which changes to red at 20 volts, and to orange at 21 volts. The measured P.D.'s must be corrected for the effect of the contact potential between cathode and grid (the grid acts here as anode): this correction amounts to about 2·5 volts for the valves mentioned.

Experimental proof of electron spin

Expt. 87. A soft iron rod about 8–10 cm long and 0·5 cm diameter is suspended by a thin fibre so as to be exactly central in a coil of 3000 to 4000 turns (fig. 7.5). A small mirror (silvered cover-

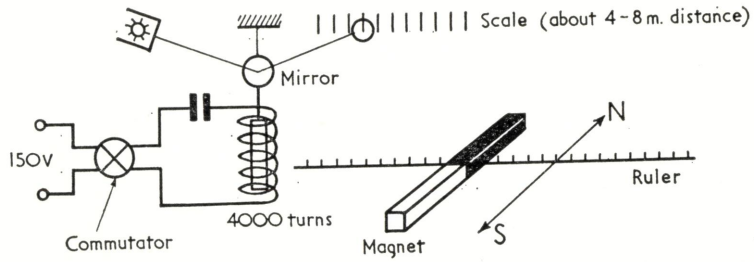


Fig. 7.5

slip) is firmly attached to the rod. So as to equalize any inevitable inaccuracy in the suspension, a bar magnet is placed accurately in a N–S line near the iron rod. If the magnet is moved parallel to itself in an E–W line, the result is that at the rod the earth's magnetic field can be exactly compensated. The magnet is first placed close to the coil. As the voltage is switched on, the iron rod begins to make oscillations which are brought to a maximum by turning the switch in time with the oscillations. At this maximum the position of reversal of the spot of light on the scale is read. These readings are repeated for increasing distances of the magnet from the coil. A curve with a definite minimum is thus obtained (fig. 7.6). The distance of this curve from the horizontal axis gives

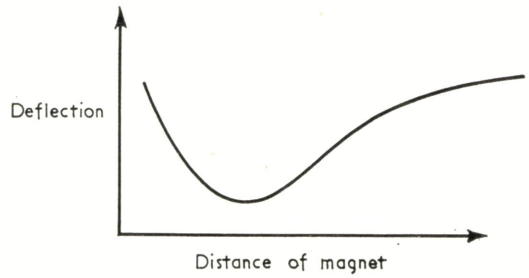


Fig. 7.6

the distance which is caused by the spin of the electrons (Athen, 'Theory and exact calculation', PRASCHU, 1950/11, p. 329).[1]

Diffraction of electrons

Expt. 88. The principle of an apparatus for interference of electrons is shown in fig. 7.7.

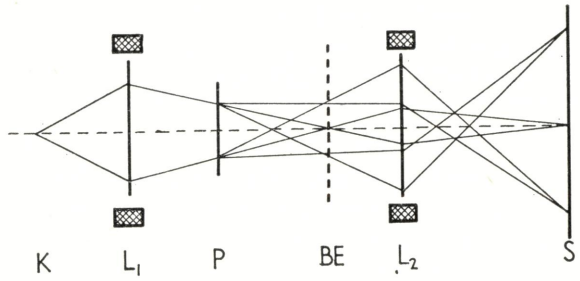


Fig. 7.7

The electrons coming from the cathode K are focussed by the magnetic lens L_1 on the screen BE. A substance P deflects the electrons along directions characteristic of that substance. A sharp set of interference spots appears at BE, which by means of the magnetic projection lens L_2 is shown magnified on the image screen. For this image screen one may use the cut-off bulb of an old television tube. For the construction of a better apparatus see Balling-Saur, PRAXIS, 1956/5, p. 124.

[1] This is a very difficult experiment on the gyromagnetic effect. See Schröder, *Atomphysik in Versuchen*; Stoner, *Magnetism and Matter*, London 1934; Bates, *Modern Magnetism*, Cambridge 1951.

8
Nuclear physics

A. The use of ionizing radiations: factors affecting safety and health

I. General

Before undertaking any work involving the use of ionizing radiations whether from radioactive substances or from equipment capable of generating X-rays, reference should be made to the following:

(*a*) *Code of Practice for the protection of persons exposed to Ionizing Radiations in Research and Teaching* (H.M. Stationery Office, 1964).

(*b*) In the case of schools, teacher training colleges, and technical colleges, Notes I.R.N. and Notes I.R.X., obtainable from the Department of Education and Science, Curzon Street, London W.1.

Use of X-ray equipment

All apparatus operating at 5 kV or more must be screened

5–50 kV	1 mm lead
50–75 kV	2 mm lead
75–100 kV	3 mm lead

The screening must entirely surround the X-ray tube (or any apparatus, such as gas-discharge tubes, capable of generating X-rays). Reference should be made to Notes I.R.X. obtainable from the Department of Education and Science.

No X-ray generating apparatus operating at more than 5 kV

may be used without prior authorization by the Department of Education and Science.

A limit is set by the Department at 50 millirems as the maximum dose per year of external radiation from radioactive sources and X-rays combined.

II. Definitions

The unit of exposure dose is the Röntgen.

1 Röntgen, R, produces in each 0·001293 g of air 1 E.S.U. of ions of each sign. 1 R = $2{\cdot}08 \times 10^9$ pairs of ions. If the mean ionization energy for one ion pair is taken as 34 eV, it follows that 1 R = 87·7 ergs/g of air or 93 ergs/g of water.

The absorbed dose of any ionizing radiation of any kind is the energy ΔE which is delivered by ionizing particles at a particular place in the radiated substance, divided by the mass Δm of that substance.

The unit of the absorbed dose is the rad (radiation absorbed dose); 1 rad = 100 ergs/g. This equation holds for all kinds of ionizing radiations including neutrons. (The Röntgen is defined only for X-rays or γ-rays, and is applicable with these only up to quantum energies of 3 MeV.)

1 rem (rad equivalent man), r, is the dose of any kind of ionizing radiation which in similar circumstances causes the same biological action as 1 rad of X-rays at 200–250 kV.

Activity: 1 Curie, c, is the activity of a quantity of a radioactive atom which undergoes $3{\cdot}700 \times 10^{10}$ disintegrations per sec. 1 g Ra = 1 c Ra.

III. Sealed (closed) sources

Values for maximum permissible doses are based on the recommendations of the International Commission on Radiological Protection (I.C.R.P.) adopted in September 1958 and 1959.

For persons who do not have to use radioactive sources regularly the following are the highest permissible doses recommended:

For radiation of the whole body

Over 18 years of age	1·5 r/year
16–18 years	1·5 r/year
Under 16 years	0·5 r/year

For radiation of the hands and forearms

Over 18 years of age	7·5 r/year
16–18 years	7·5 r/year
Under 16 years	7·5 r/year

The I.C.R.P. has also recommended that the average dose received by the whole population from man-made radiations should not exceed 2 rems up to the age of 30 years (inclusive of dosage received from medical exposure).

Department of Education and Science Notes I.R.N., which set out the requirements of the Department for approval of the use of radioactive substances for work at schools level, set a limit of 0·05 r as the external radiation which may be received by any one pupil as the result of experiments in schools.

The following table shows how long certain types of radiation take to attain a dose of 0·05r.

Nuclide	*Distance from source*	*Activity*	*Duration of radiation to give dose of 0·05 r*
Ra 226	1 m	10 μc	6000 hours
Co 60	1 m	10 μc	370 hours
I 131	1 m	10 μc	21500 hours

These figures are for sealed sources.

It is evident that at a distance of, say, 1 cm the limiting dose may easily be exceeded. Forceps and tongs should be used so as to reduce the dose received; these should be kept for this purpose only.

Sr 90/Y 90 give off particles which will penetrate 4 mm thickness of glass or paper. Special protection is therefore needed for mucous membranes. The eyes should be protected by special glasses.

For dosimetry of X-rays and γ-rays, see Hecht, PRAXIS, 1958, vol. 10, p. 268.

IV. Open sources

Open sources are a very different matter. With these the highest activity for use in schools is limited not only by the quantity of

radiation given out, but also, in the worst case, by the penetration of part of the source or its decay products into the body.

Experiments with open sources of α-particles, other than the usual laboratory salts of uranium and thorium, are forbidden in schools, and limits are set, in Notes I.R.N., on the activities which may be used per experiment and on the total activity of the sources which may be held by a school or by other establishments working at schools level.

It should be noted that no pupil below the age of 16 is permitted to carry out experiments with radioactive substances other than those which require him to use only the usual laboratory compounds of potassium, uranium, and thorium.

Open sources should always be handled with the same precautions as are used with concentrated acids. Preferably they should be used only on a bench with a non-porous surface, or one covered with several sheets of paper which can later be destroyed: the sources should be handled only with tools reserved for this purpose. If there is any possibility of the evolution of gas or vapour, or gaseous radioactive decay products, the experiments must be done in a fume cupboard with a good updraught. After each experiment the hands should be well washed, and dried with paper handkerchiefs which are then destroyed: or rubber gloves should be worn. Smoking and drinking in the laboratory should be strictly forbidden. Radioactive solutions should obviously never by sucked up into pipettes with the mouth.

Waste should not be thrown into the general refuse bin, but into special ones, which should be kept separate from others until their activity has decayed sufficiently; this, even with the relatively short-life I 131 and P 32, lasts for several weeks. As a general rule the decay time may be taken as ten times the half-life. Unwanted radioactive solutions should be left as long as possible and greatly diluted before being poured away. From this it follows that all vessels which contain radioactive substances or solutions should be clearly labelled, as to contents and date.

V. Storage

Notes I.R.N. give guidance on storage.

The storage of radioactive sources should be so arranged that unauthorized and uninstructed persons, including colleagues, do

not have access to them. It is best if they are stored in a special cupboard which must in any case be away from any commonly used rooms. The cupboard must be suitably labelled and where γ-emitters are being stored, either the source or the cupboard must have a lead lining.

VI. Possibility of biological damage to future generations

The development of embryos may very easily be damaged by ionizing radiations. It must be accepted that recovery after being exposed to radiation is not possible, and that successive doses are cumulative and may show themselves as mutations in the genes. Careful investigation gives a value for the amount of radiation due to natural sources absorbed by the generative organs in man. It is about 3 rad in 30 years.

X-ray diagnostic examination adds about		22% to this dose
X-ray apparatus in shoe-shops	,, ,,	1% ,, ,, ,,
Watches with luminous figures	,, ,,	1% ,, ,, ,,
Television sets	less than	1% ,, ,, ,,
Radioactive fall-out from experimental nuclear explosions	less than	1% ,, ,, ,,

British determinations require that the total radiation dose between conception and the age of 30 years, in addition to naturally occurring radiation, shall not exceed 50 r. This corresponds to about 0·03 r/week. This however is to be the highest attained among any group of 50 men. The International Commission for Radiation Protection (1958) lays down for the general population that the average permissible dose to the gonads shall not exceed 5 r over a period of 30 years (additional to that from natural sources and to the lowest medical dose).

It will doubtless be noted that the dose received by man from man-made sources in the fifty years since the discovery of ionizing radiations already amounts to about 25% of that from natural sources.

It is also desirable to reduce these figures when possible, or at least to increase them as little as may be consistent with the demands of technology and industry. The dose should never be exceeded in educational work.

How anxious scientists are to avoid every unnecessary dose additional to the natural radiation, is shown by many recommendations. For example, X-ray apparatus in shoe shops should be discontinued. Also (on the influence of watches with luminous dials in raising the radiation dose): 'We think that the supply of instruments with luminous dial-plates might be investigated. For most people they are not necessary' (Medical Research Council: *The Hazards to Man of Nuclear and Allied Radiations*, 1956, p. 67).

VII. Conclusions

From these considerations and data follow certain rules regarding the employment of radioactive sources in schools.

1. Experiments involving radioactivity shall be undertaken only when they are strictly necessary for the course of instruction. They should never be done for the sheer joy of the experiment or desire to create a sensation.

2. Each experiment should be done with no higher activity than is really required, and below which the experiment would not succeed.

3. The experiments are not intended to be done by members of the class, who should be kept as far as possible from the radioactive sources.

4. The teacher should be careful not to exceed the dose of 50 millirems of external radiations in a year.

5. It is desirable that there shall be near any apparatus for experiments a meter calibrated in mr/hour to keep a continuous check on the dose rate near the apparatus: this should give accurate readings in the significant range of from 0·1 to 0·2 mr/hour.

A comprehensive bibliography is given in the Code of Practice mentioned earlier.

B. Apparatus for experiments in radioactivity

Ions as nuclei for condensation

Expt. 89. A flask is closed with a cork, through which passes a glass tube drawn out to a jet. Water in this flask is boiled on an electric hotplate. The steam coming out of the tube produces a thin

cloud. If a glowing piece of wood is held in this steam, the cloud becomes noticeably more dense.

If a bunsen burner is used to boil the water the jet should be at the end of a long horizontally bent glass tube. This ensures that ions from the bunsen flame do not produce the cloud.

Expt. 90. If a beaker half full of water is boiled by means of an immersion heater, and the heater is then removed, the steam in the space above the water can be made visible by means of a glowing splinter or a spark gap (operated by means of an induction coil).

Expt. 91. Instead of the splinter of Expt. 89 or of the spark gap of Expt. 90 one may use a radioactive source, e.g. 5 μc Ra 226 or 5 μc Am 241. The appearance of the clouds may be made visible to a large class by projecting them.

Expt. 92. A well-dried filter flask, closed at the top, is quickly pumped out as much as possible by means of its side tube; nothing is to be observed.

Some water is then placed in the flask and shaken around. Now, on pumping out, clouds are formed. These are noticeably thicker if, before pumping out, a glowing splinter or a radioactive source is held in the flask (Bindseil, PRAXIS, 1953/8, p. 237).

Essential apparatus for experiments on radiations from atomic nuclei includes the ionization chamber, the point counter, and the Geiger-Müller tube.

Construction of cloud chambers

(*a*) *Expansion chambers*

Expt. 93. A simple cloud chamber may be constructed as follows:

A round-bottomed flask with a short neck is provided with a rubber bung, from which projects a wire bearing a radioactive substance; this is arranged to be in the middle of the flask. The bung also has a stop-cock passing through it. The air pressure in the flask is raised by pumping in air: time is allowed for room temperature to be regained, and the stop-cock is then opened. The

cooling effect so obtained produces clouds. Near the radioactive substance, e.g. 0·1 μc Ra, the tracks of α-particles may be seen (Hofmann, PRAXIS, 1955/9, p. 232).

Expt. 94 (fig. 8.1). A large hole is cut in the screw tin lids of two marmalade jars, which are then soldered together back to

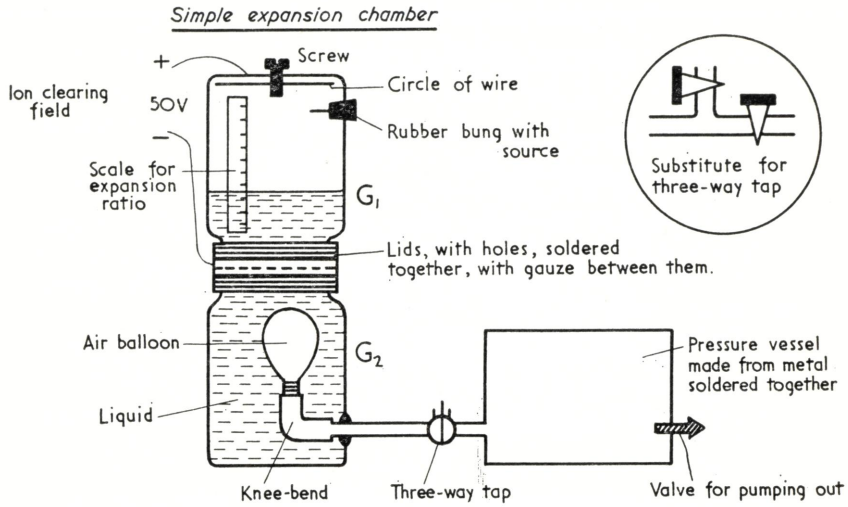


Fig. 8.1

back with a piece of wire gauze between them. A hole is made in the bottom of jar G_1, and another, larger one, in its side. The drilling of these may be done by means of a brass tube with teeth at the end fed with grinding powder: this is carried out in water to keep the glass cool. In the side of jar G_2 another hole is made, so that a six-inch stop-cock tube may be passed through it and fixed with a water-resisting cement. On the inner end of this tube is screwed a knee bend to which is attached a rubber balloon. By means of a screw, a piece of copper wire bent into a circle is fixed inside the bottom of G_1; the tube from G_2 is connected through a three-way tap with a metal vessel provided with a bicycle valve for pumping in air. The jars are screwed on top of one another, and are filled with a 1 : 1 mixture of alcohol and water, containing a little Indian ink and sodium chloride. A scale is fixed to the side, so that the best expansion ratio (between 1·33 and 1·35)

may be easily determined. The use of the cloud chamber is quite straightforward. A 0·1 μc Ra source should suffice (*Scientific American*, April 1956, p. 156).

Expt. 95. The cloud chamber of Prof. Bauer works in a similar way. Its construction and method of use are shown in Fig. 8.2 (Feldt, MNU, V/1, p. 46). A 0·1 μc Ra source may be used.

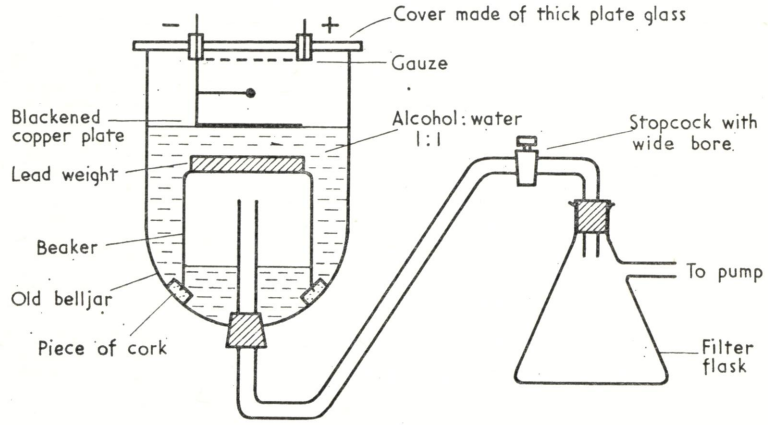


Fig. 8.2

Expt. 96. A home-made cloud chamber for individual and group observation is described by Herr Seus in PRAXIS, 1952/8, p. 220. It is made from a brass cylinder 13 cm in diameter, which is closed at each side by a rubber ring and a glass plate (fig. 8.3). A tube of felt is arranged concentrically inside the brass tube so that it fits tightly against the glass plates. Copper wires pass into the brass tube but are insulated from it. Inside the felt tube these are bent into circles lying parallel to the glass plates: they provide the ion clearance field. A vacuum pump is connected to a third opening in the brass tube. The necessary

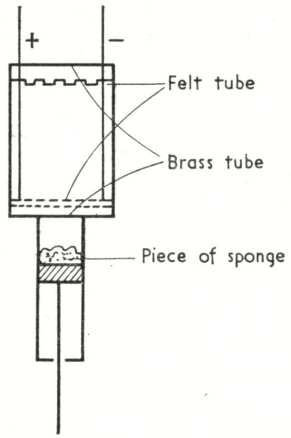


Fig. 8.3

vapour in the chamber is obtained from a small sponge, fastened to the piston and soaked in a mixture of methyl alcohol and water (1 : 1). The radioactive source is fixed to the felt tube. The best expansion ratios are:

for α-particles 1·31 to 1·38
for β-particles 1·25 to 1·31
These may be marked on the piston-rod.

To obtain vapour trail endings in the chamber, the source should be enclosed in tinfoil 0·01 to 0·02 mm thick. A 0·1 μc Ra source should be adequate.

Expt. 97. Direct observation. The chamber is illuminated with slightly divergent light: the trails produced by the radioactive source may be observed with the chamber either vertical or horizontal. A 0·1 μc Ra source may be used.

Expt. 98. Projection. The chamber is held vertically by means of a clamp. For projection on to the wall of the room, either a plane mirror or a prism may be used. See fig. 8.4. The same source will suffice.

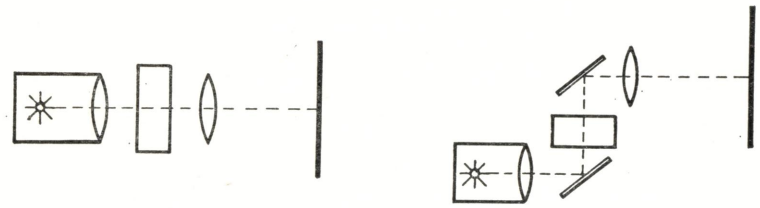


Fig. 8.4

Expt. 99. Photography. So that direct light may not enter the camera, the cloud chamber is illuminated by two projection lamps, which are arranged symmetrically about the axis of the chamber. See fig. 8.5. A 0·1 μc Ra source should be adequate (Seus, PRAXIS, 1952/11, p. 331 and 1953, photo, p. 9).

(b) Continuous cloud chambers

Expt. 100. The action of a continuous cloud chamber is due to

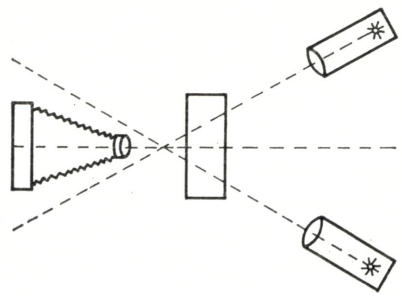


Fig. 8.5

the production of the necessary supersaturation at a given level by means of a large temperature gradient, from room temperature to that of solid carbon dioxide (Werz, PRAXIS, 1953/4, p. 121).

This chamber however will work only with weak sources since medium and strong sources soon use up the supersaturated layer, and give a thick cloud in the chamber, in which new trails are difficult to see. It is, however, very good for showing the natural radioactivity of the air and the effect of cosmic rays. See fig. 8.6 (Seus, PRAXIS, 1954/1, p. 1).

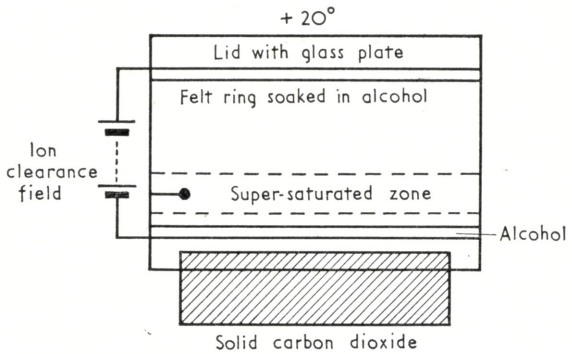


Fig. 8.6

Expt. 101. A glass cylinder 12 cm high and 10 cm in diameter has a tin plate, blackened on the upper side, stuck to its lower end with Sellotape. In contact with this plate on the lower side is a tin can, 4 cm high and 10 cm wide, full of solid carbon dioxide; this can is surrounded by a larger can 10 cm high and 12 cm wide, full

of glass wool for heat insulation. This last can stands on wooden blocks for further insulation from the bench. Just inside the top of the glass cylinder is a felt ring, stuck to the sides and moistened with a 1 : 1 mixture of methyl alcohol and water. The glass cylinder is closed at the top by a piece of plate glass. An electrostatic field to remove old tracks is produced by rubbing this glass on the top with silk.

The account gives a critical comparison of the relative merits of expansion and of continuous cloud chambers (Seus, PRAXIS, 1954/1, pp. 1, 2, 3).

Other easily made chambers are shown in figs. 8.7 and 8.8. These may be used with 0·1 μc Ra sources.

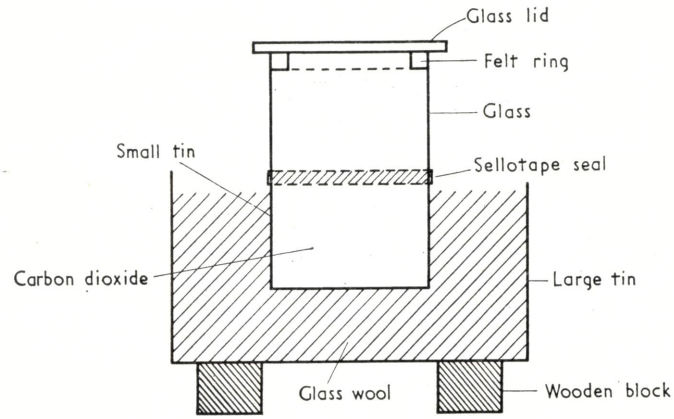


Fig. 8.7

Expt. 102. If a metallic mirror is placed at the bottom of these chambers to reflect the light, it may be possible to project the cloud tracks (Seus, PRAXIS, 1955/5, p. 137). The same 0·1 μc Ra source may be used.

Neon lamp as indicator of reduction of striking voltage by γ-rays

Expt. 103. The voltage applied to a neon lamp is adjusted so as to be only very slightly below the striking voltage. The neon lamp is then exposed to γ-rays from a radioactive source, e.g. any closed γ-source of about 5 μc activity: the quanta of energy obtained

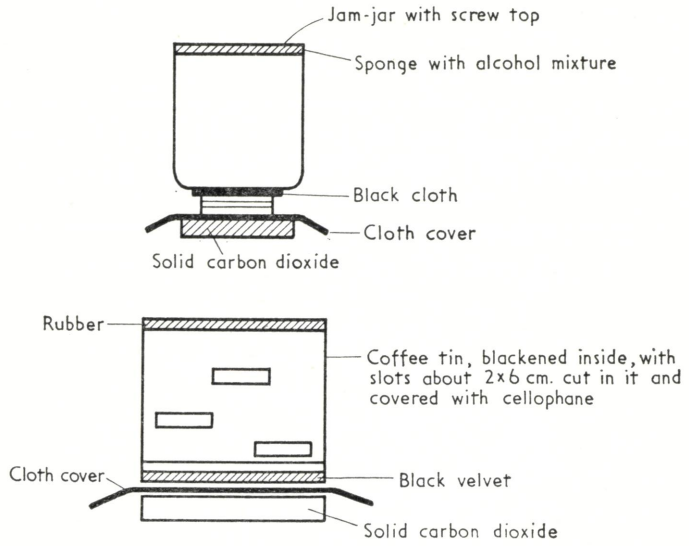


Fig. 8.8

from these are sufficient to bring the lamp up to its striking point. When the lamp strikes, the voltage falls below that needed for striking again, and the lamp goes out, so that only a very short burst of current flows: this may be easily seen as a flash in the lamp or may be made audible by means of a loudspeaker (Reimers, PRAXIS, 1954/6, p. 185).

Greinacher's spark counters

Expt. 104 (fig. 8.9). In these, α-, β-, and γ-rays are counted by means of the sparks which they produce. When an ionizing radiation passes between two electrodes maintained at a high potential difference, a spark takes place. Amplification of the effect elec-

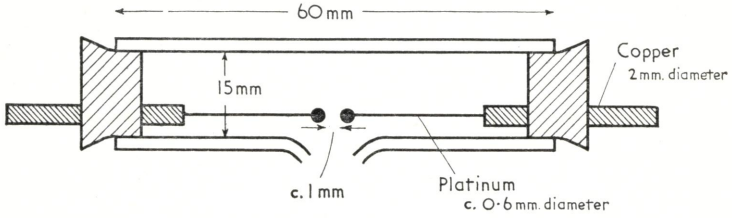


Fig. 8.9

tronically is not necessary. If two small and equal platinum spheres are used as electrodes, their polarity has no effect. The counter will work equally well on an alternating voltage. The spark takes place only when the voltage exceeds some particular value.

The spark gap is adjusted so that sparks just do not take place in the absence of ionizing radiations: this may be accomplished by altering the length of the gap, the voltage applied to the electrodes, or the air pressure.

If a wire, used as an aerial, is connected with a neon lamp and a pair of headphones (fig. 8.10), the sparks may be made audible

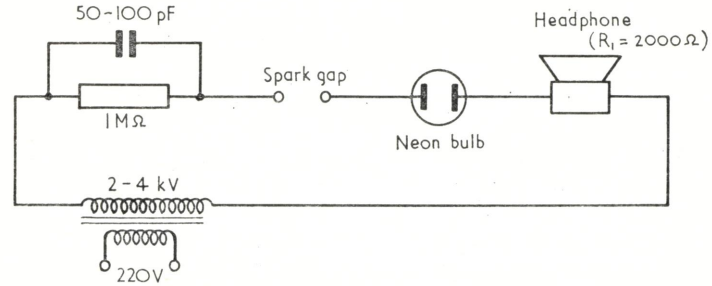


Fig. 8.10

in a radio receiver. This simple apparatus is most useful for determining the range of particles. Not more than 10 μc of any nuclide will be needed (Schuster, MNU, V/2, p. 104).

Greinacher's hydraulic counter

Expt. 105 (fig. 8.11).[1] A jet of water about 1 mm in diameter comes from a smooth glass nozzle connected by tubing to the water tap, and strikes a sheet of rubber stretched across one end of a tin can. The distance is adjusted so that the jet just does not break up into drops; no rustling noise is heard. (If a vibrating tuning fork is applied to the nozzle, the sound obtained should be loud.) Immediately in front of the nozzle, and very close to the jet, is an iron nail bent at right angles and with the pointed end perpendicular to the jet and acting as an electrode. This electrode is connected through a resistance of about 100 megohms to a source of voltage of about 2000 volts. Each ionizing particle which passes between the electrode and the jet causes a momentary fall

[1] *Translator's Note:* Owing to the danger arising from the juxtaposition of water and a high voltage, some teachers may regard this experiment as hazardous.

of the potential of the electrode, which is heard as a knock on the sheet of rubber.

This 'counter' may also be operated on alternating current by means of a step-up transformer (600 and 12 000 turns). The 50-cycle

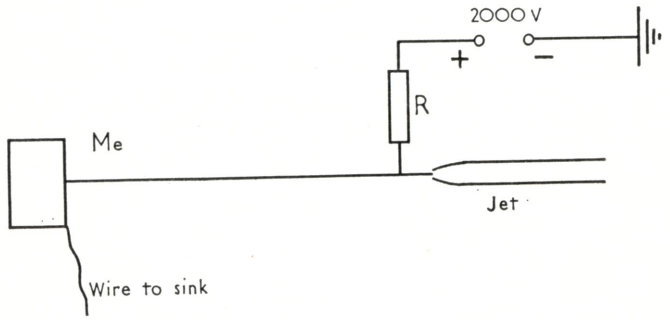


Fig. 8.11

note is heard loudly. If the rubber is brought nearer to the nozzle this note becomes less audible, and the 'counting knocks' may then be heard, but not so well as with direct current. If a neon lamp is used instead of the resistance, then the ionizing particles will cause the lamp to flash (Hein, MNU, V/6, p. 367).

Point counter

This consists of a cylindrical metal electrode, having along its long axis a second needle-shaped electrode ending in a point or a small sphere. For the cylindrical electrode it is convenient to use one of the small aluminium cylinders in which 35-mm photographic film is sold.

Expt. 106 (fig. 8.12). A circular hole is made in the bottom of the cylinder and a needle-shaped electrode, e.g. a pin, is fixed in the

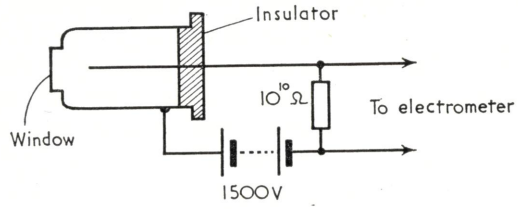


Fig. 8.12

screw end by means of a cylindrical piece of a good insulator. The electrode must have a slightly oxidized surface and be accurately placed along the central axis of the aluminium cylinder. The distance of the point from the front surface must not be greater than the diameter of the counter. If the opening in front of the point is covered with mica, aluminium foil, etc., then the counter may be used to study the effect of various radiations, e.g. α-particles may be filtered out by appropriate thicknesses of 'window' from any radiation being investigated. The voltage needed varies, according to the gas pressure, between 100 volts and several kilovolts (Inderthal, PRAXIS, 1955/5, p. 113).

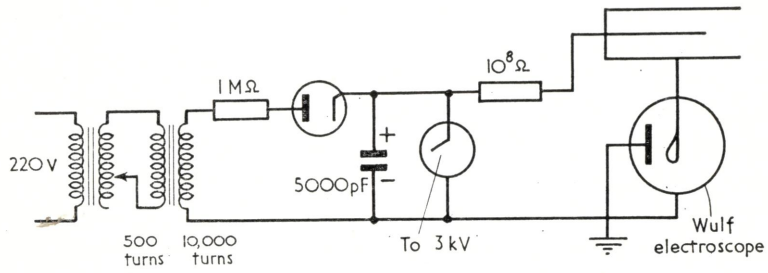


Fig. 8.13

The circuit shown in fig. 8.13 for the point counter is given by Bosch in PRAXIS, 1952/8, p. 227. Not more than 10 μc should be needed.

Geiger-Müller counter tube

For theory, see textbooks and also Inderthal, PRAXIS, 1955/5, pp. 113/119.

Expt. 107. This is most easily made from a cylindrical metal tube 6 to 8 cm long, 3 cm in diameter, and with walls 1 mm thick: the tube may be of zinc, brass, or aluminium, and is closed at each end, so as to be vacuum-tight, with a good insulating material: this latter also holds the counter wire (e.g. steel about 0·1 to 0·2 mm diameter) down the centre of the tube and insulates it from the sides (fig. 8.14).

Since the working voltage increases with the pressure of the gas in the tube, this pressure must be made low. The 'dead time' of

the counter tube increases as the square of the diameter. The lower limit for the diameter is about 2 cm.

Instead of using metal for the outer cylinder one may use a thin-walled glass cylinder coated on the inside with copper or silver (by

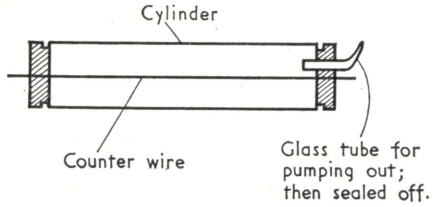


Fig. 8.14

evaporation or by chemical means). It is still more easy to coat it on the inside with a thin layer of graphite by using 'Aquadag' or 'Hydrokollag'. The counter tube described here operates only with a negative voltage of some kilovolts on the cylinder. The output resistance, across which a voltage is developed when the tube is traversed by an ionizing particle, is of the order of 100 megohms (an Indian ink line on drawing paper) (Inderthal, PRAXIS, 1955/5, pp. 113 ff.).

In practice the construction of Geiger-Müller counter tubes is hardly worth while, since the supply of all kinds of tubes for different purposes is very great, and hence the cost of such an article is no great difficulty (Seus/Ulbricht, PRAXIS, 1959/4, p. 92).

Expt. 108. Fig. 8.15 shows a rectangular piece of insulator with connections to a Leybold 'Tracerlab' counter tube and a radio receiver (Seus, PRAXIS, 1958/5, p. 122).

K socket for cathode of counter tube
A socket for anode of counter tube
H socket for third pin of tube
1 terminal connected through 50 MΩ to − pole of high tension
2 earthed terminal
3, 4 terminals connected to pick-up of radio set
$R \approx 100$ MΩ (½ W)
$C = 500$ pF (1500 V ~)

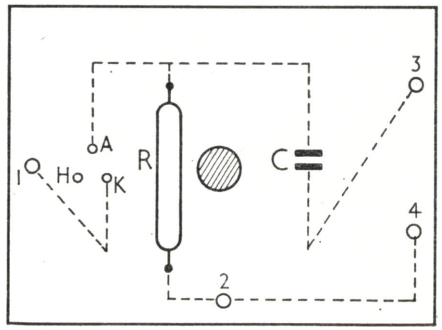


Fig. 8.15

Expt. 109. Battery operated Geiger-Müller counter.

A 2-volt accumulator serves as the source of direct current. The voltage is stepped up by means of a car radio vibrator and a suitable transformer so as to give an output voltage of about 500 volts (fig. 8.16). This is then applied, in the counter circuit, to a counter

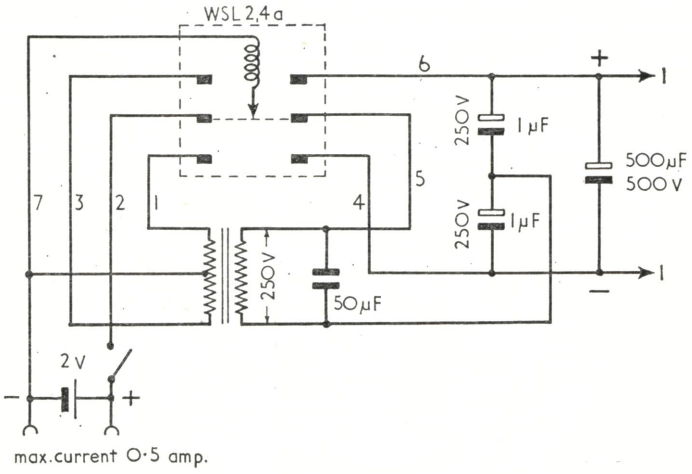


Fig. 8.16

tube having a working voltage of between 400 and 650 volts. A second pair of terminals, 2, is included in the counter circuit so that alternative sources of voltage may be used (fig. 8.17) (Voit, PRAXIS, 1956/11, p. 310).

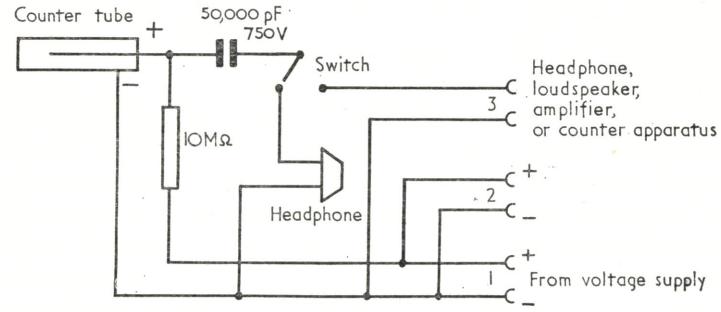


Fig. 8.17

Integrating measurement

Expt. 110. Sometimes the number of impulses per minute is too great to be counted. In this case the impulses from the point counter or the Geiger-Müller tube may be passed to the input of an amplifier which has a milliammeter to measure its output. The current in the output circuit depends directly on the frequency of the input impulses; this gives an integrated value. Two simple arrangements for doing this are shown in fig. 8.18 (Voit, PRAXIS, 1958/10, pp. 261 and 262).

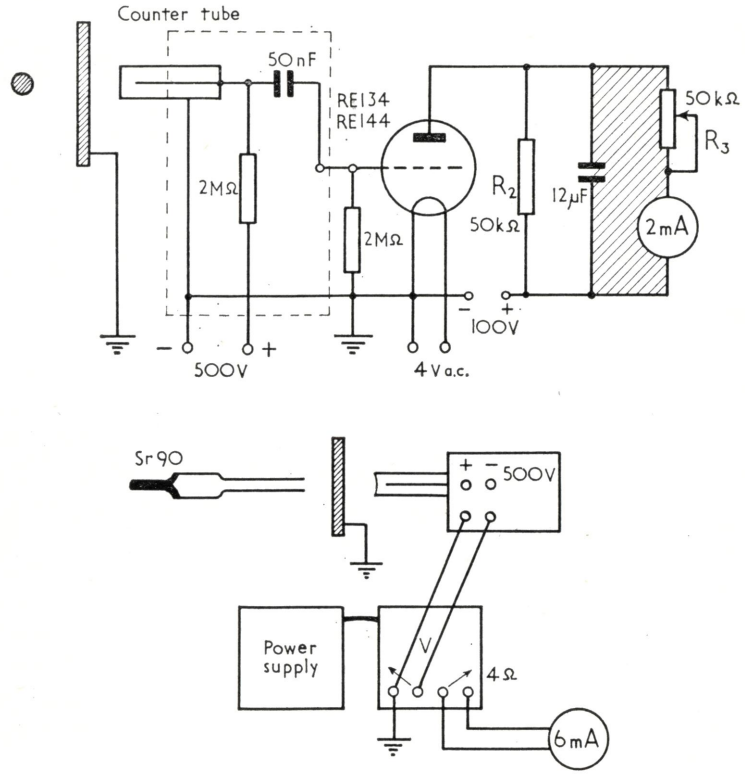


Fig. 8.18

Multivibrator quench circuit

Expt. 111. A multivibrator has the property of delivering from its output capacitor for further amplification or measurement im-

pulses of equal length and strength which are independent of the duration and strength of the input impulses.

A multivibrator quench circuit, like that shown in fig. 8.19, sends back also a powerful square-wave form impulse to the coun-

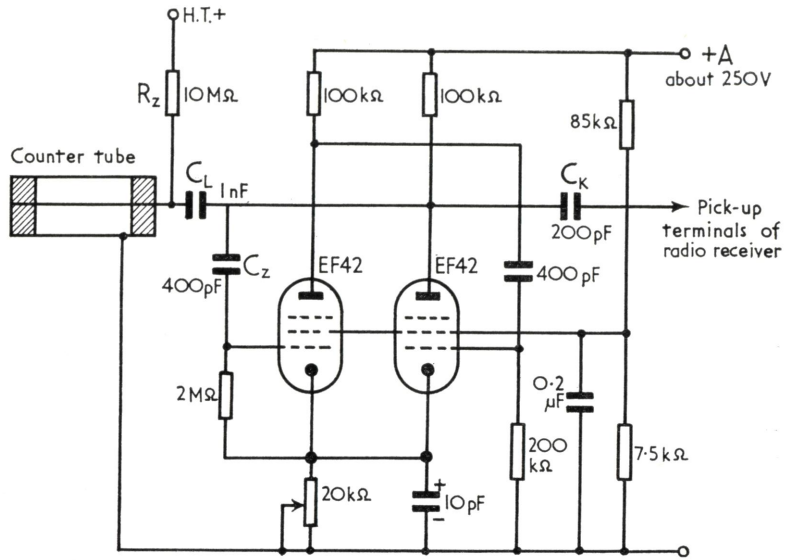


Fig. 8.19

ter tube which reduces the voltage below that needed for the tube to strike and hence quenches the discharge which initiated the impulse. This arrangement is particularly recommended for experiments with spark counters and air-filled Geiger counters (Inderthal, PRAXIS, 1955/5, p. 117).

Counter mechanisms

Expt. 112. If small impulses have to be measured for a long period of time (and this is often necessary to get accurate results) the fatiguing counting of the impulses may be done by a mechanical counter. Instead of the milliammeter used in Expt. 110, a mechanical counter is connected through a relay to the output of the amplifier. A Post Office relay, which can be obtained very cheaply from surplus equipment dealers, may be used. For higher impulse frequencies mechanical counters are not suitable. Instead, one has

to use either intermediate electronic reducing stages before the mechanical counter or purely electronic counting by means of dekatron tubes such as E1T. Such devices are available commercially in great numbers.

Photographic films as detecting devices for ionizing radiations

Photographic films are also suitable for detecting ionizing radiations. They integrate the radiations which pass through them during the exposure time. The amount of blackening, produced under particular conditions by the radiation and visible after development, increases with the quantity of radiation falling on them (the 'dose'). The blackening is, however, a linear function of the dose only for particular emulsions (e.g. the photographic plates for radiation measurement manufactured by Dr C. Schleussner's Adox Photographic Works, Frankfurt on Main) and then only within certain limits for the quantity of the dose and the energy of the radiation. However, photographic plates have the advantage that, after suitable development, tracks of individual radiations may be observed under the microscope (e.g. with nuclear track plates manufactured by such firms as Ilford and Leybold).

A single α-particle gives a noticeable blackening. X-ray plates are good for showing β- and γ-rays, and one can also obtain quite good results with cheap lantern plates.

C. Experiments with radioactive sources

Background count

Expt. 113. An apparatus for detecting ionizing radiations is set up, without having any radioactive source near it, yet particles are counted, and are found to be distributed according to normal probability. This effect is called the background count. It is due firstly to the different components of cosmic radiation (over the sea, actually mesons, electrons, and neutrons) and to the secondary radiations produced by these. The second source of background count is the radiation from the surroundings (actually γ-rays), which is produced by the traces of thorium and radium almost

always present in the ground. Inside buildings these two sources are responsible for about half of the total background count. It is important that the background count should be determined before and after any series of observations with radioactive sources.

Concept of half life: experimental analogy

Expt. 114 (fig. 8.20). A d.c. voltage of at least 150 volts is connected to a Morse key and a capacitor of 32 μF. The latter is then

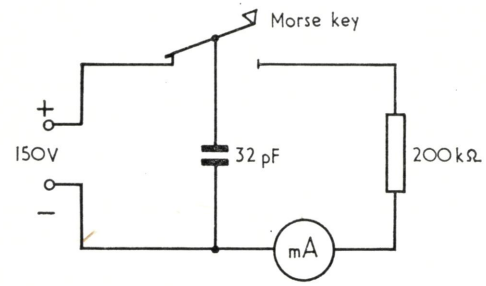


Fig. 8.20

discharged through a high resistance and a milliammeter. The deflection of the milliammeter dies away exponentially. The time taken for an arbitrary current i_0 to fall to $\frac{i_0}{2}$ is measured for different values of i_0 and is compared with the calculated value.

See also similar experiments with water running out of tubes through capillary filters (Hecht-Lindberg, MNU, XII, p. 344).

Determination of half life by cloud chamber

Expt. 115. A certain quantity of air containing thorium emanation (from a special bottle, or from a bottle in which old gas mantles have been stored) is placed in the chamber; expansions are performed for a period of one minute. The number of α-ray tracks dies away rapidly (Seus, PRAXIS, 1956/12, p. 323).

Determination of half life

Expt. 116. A suitable source with a short half life (possibly Na 24) is placed at a distance from the counter tube such that the number of counts can be accurately measured. The counts per minute are

noted. According to the value of the half life, the counts must be measured at intervals of hours or even of several days: the time which has elapsed since the first measurement must be accurately determined. For these measurements it is necessary that during the whole series of experiments the 'geometry' of the apparatus must remain the same, that is the position of the counter tube relative to the radioactive source, and the position of both relative to their surroundings; or if that is not possible, the positions must be reproduced just before each measurement. The logarithm of the number of counts is plotted on a graph against the time, the background count having been carefully taken into consideration. A straight line may be drawn through the graph points, from which the half life may at once be found. It is still better to plot not the plain logarithm of the number of counts but the logarithm of the quotient of any count and the first count ($t = 0$), the background count having been subtracted from both. The maximum quantity of Na 24 per experiment is 160 microcuries.

Expt. 117. Some thorium emanation is blown into an ionization chamber and the ionization current produced by an applied source of voltage is determined by means of a Wulf electroscope or picoammeter; this becomes smaller with time. The logarithm of the frequency of discharge of the ribbon of the electroscope or of the current shown by the picoammeter is plotted as an ordinate against time. The straight line which can be drawn through the graph points shows that the radioactive decay follows an exponential law. Also from the graph the half life may be read off. (A different way of doing this experiment with the Wulf electroscope is given by Harttäg in MNU, VIII, p. 297.)

Making a spinthariscope

When α-particles strike a crystal of zinc sulphide, the considerable energy of the particles causes a flash of light lasting about 10^{-4} sec, called a scintillation. This is visible to the naked eye but is seen better with a microscope giving a magnification of about 30.

For β- and γ-rays, willemite and barium platinocyanide give better results.

Expt. 118. A simple spinthariscope is obtained if luminous hands

from an old clock or watch are observed, in darkness, through a magnifying glass (Reimers, PRAXIS, 1952/3, p. 57).

Expt. 119. The same effect is obtained if radiation from a radioactive source is allowed to fall in the dark on an X-ray screen or ultra-violet screen, or on an old luminous clock hand.

Expt. 120. Very fine effects may be obtained with the following spinthariscope. The cavity in a microscope slide is smeared lightly with gum, and this is coated thinly with finely powdered zinc blende (ZnS + 0·01% Cu). A drop of a solution of a radium salt is placed on a cover slip, and is allowed to dry: the slip is then secured on the slide by Canada-balsam and shellac so that the radium faces the zinc sulphide. The use of solutions of radium salts is forbidden in British schools, as they constitute an open source of α-radiation (Jöhnck, PRAXIS, 1953/3, p. 95).

Expt. 121. If the zinc sulphide on the microscope slide is wetted directly with the radium-containing solution, one obtains a luminous material which, when its surface is observed through a microscope or a magnifying glass, shows a bright and continuously flickering light. The use of solutions of radium salts is forbidden in British schools, as they constitute an open source of α-radiation (Jöhnck, PRAXIS, 1953/3, p. 95).

Expt. 122. A scintillating substance is prepared by mixing zinc blende with uranium nitrate in the proportion 1 : 5. Instead of uranium nitrate one may use either pulverized pitchblende or a powdered-up piece of a thorium-impregnated gas mantle. Shellac may be used as binder-material. Because of the long afterglow, these preparations must be stored in the dark (Seeger, PRAXIS, 1957/6, p. 162).

Expt. 123. Quantitative determinations of energetic α-rays are possible, with an accuracy of $\pm 10\%$, if the scintillations from the zinc sulphide screen are allowed to fall on a photocell connected to a two-stage amplifier.

INVESTIGATION OF THE RADIATION FROM RADIUM

Expt. 124. A radioactive source (e.g. a 5 μc radium source) is placed very near to a sensitive thermopile. The thermoelectric

current gives a perceptible deflection of the spot of light from a mirror galvanometer connected to the thermopile. It is evident from the direction of the deflection that the radium source is warmer than its surroundings. Before the determination both the radium source and the thermopile must be left in the same place for a long time to come to room temperature. If the radium source is enclosed in some thin black paper, the deflection obtained will be greater (Seus, PRAXIS, 1957/2, p. 37).

Expt. 125. A simple electroscope is charged and a radioactive source (from which α-particles have not been filtered out: Leybold's radium source is convenient) is brought up to a distance of about 2 cm from the cap of the electroscope. The electroscope is discharged in a short time. The electroscope may have a zinc plate placed on it, so as to obtain a result like that produced when the plate is irradiated with ultra-violet rays, but with discharge by the radiation from radium, the sign of the charge on the electroscope does not matter. In contrast to the discharge by u.v. rays, one can slow down the radioactive discharge by directing a strong blast of air between the source and the zinc plate, the air being blown at right angles to the direction of the radioactive radiation. We are therefore concerned here with ionization of the air.

Expt. 126. Radiation from radium is allowed to fall on the air dielectric of a charged plate capacitor, which is connected to an electroscope to measure the voltage. The capacitor is slowly discharged. If the total capacity of the system and the time are known the quantity of electricity which passes during the discharge may be found.

Expt. 127. The discharge which occurs in Expts. 125 and 126 is prevented if a piece of paper about 0·1 mm thick is held in front of the radium source. Evidently the radiations responsible for the ionization of the air in these experiments are not able to penetrate a thin sheet of material of this kind.

The discharge is also prevented if the source is held about 5–10 cm away from the capacitor or from the cap of the electroscope.

The path length of these ionizing radiations is thus only a few centimetres in air.

Expt. 128. The radioactive source of about 5 μc is set up about 1–2 cm from the mica window of a Geiger tube. The voltage is now raised from zero to a value such that the radiation just begins to be detected, preferably acoustically. The source is now removed to a distance of about 10 cm and the voltage is adjusted below the normal working voltage so that hardly any counts are registered. If the average of the two voltages thus obtained is then applied to the Geiger tube, it will act accurately as a proportional counter. This may then be used to determine the path length of the radiations. The experiment may also be done with a point counter or a ribbon or leaf electroscope as indicator, though naturally with suitably larger voltages.

Expt. 129. The radium source of about 5 μc is placed about 10 cm from the mica window of a Geiger counter (or a suitable distance from the opening of a point counter). The voltage is first adjusted so that the device used gives proportional counts. The voltage is then slowly raised. The counter once more begins to count. If one now tries to stop the counting by interposing paper or thin cardboard, the experiment fails. This is due to the fact that there must be another kind of radiation from the radium. That radiation must therefore consist of at least two components, which have different ionizing powers and different path lengths in substances such as air.

Expt. 130. If the voltage in Expt. 129 is made only just high enough for the two components of the radiation to give a count, then aluminium foil may be used to show that these two components are not equally absorbed. A few millimetres of wood, glass, or even lead are sufficient. The voltage of the Geiger counter or point counter is now increased—with the Geiger counter to the normal working voltage and with the point counter to about 3000 volts—counts are again registered. These are now due to a component of the radiation which is not fully absorbed even by several centimetres of lead. Result: the radiation from radium consists of three clearly separable components (α-, β-, and γ-rays).

Expt. 131. A brass cylinder is put over the 5 μc radium source container, and can carry absorption foils. The radiation which is not absorbed can be detected with a Wulf electroscope or a pico-ammeter, and its ionizing power determined. The value of the absorption foils is measured in milligrams per square centimetre. The experiment is carried out with several substances (cigarette paper, thin aluminium foil, mica). All the materials are used in increasing thicknesses and the series of results for each substance is plotted on semilogarithmic paper (reading of the recording apparatus against thickness of absorbing material). Each series of results shows the same features: first a sudden fall of intensity, then an exponential fall of only small slope. The conclusion is that one component of the radiation gives strong ionization and is easily absorbed; the second gives less ionization but has higher penetrating power. From the curves obtained, the mass absorption coefficient can be calculated; it is the same for all the usual absorption materials. The first steep part of the curve gives the sum of the effects due to both components. After the ionization due to the β-rays has been subtracted, the remainder is that due to the α-particles. Finally the effective cross-section of the atoms as regards absorption may be calculated (Stocker, PRAXIS, 1957/4, p. 85).

Expt. 132. Becquerel allowed the radiation from a radium source to pass through slits B and C in two cylinders of lead lying one inside the other (see fig. 8.21). These cylinders were placed be-

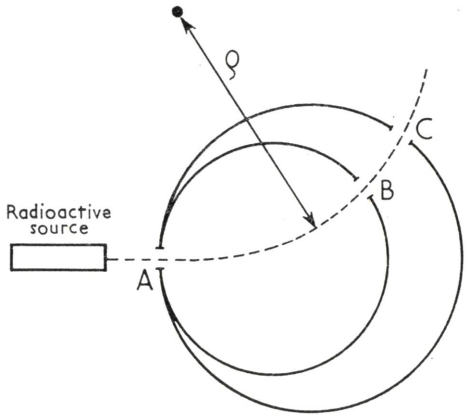


Fig. 8.21

tween the pole pieces of an electromagnet so that the lines of force were parallel to the surfaces of the cylinders. The Geiger counter was placed opposite slit C. The direction of the magnetic field was adjusted so that only α- or only β-particles were received at the counter tube in consequence of their deflection by the magnetic field. The two kinds of particle were distinguished by holding a thin piece of aluminium foil in front of the counter. The velocity of these β-particles may be calculated from the classical equation $v = \frac{e}{m}\rho\beta$, ρ being the radius of curvature of the path in the magnetic field. Values above that of the velocity of light may be obtained, since relativity theory has not been taken into account. The particles are shown to be negatively charged by the direction of the curvature. The experiment may be attempted with a 5 μc Ra source (Zita, MNU, XI/9, p. 421).

Expt. 133. The γ-rays, the hardest and most penetrating component of the radiation from radium may have their penetrating power determined in the same way as for β-particles by passing them through increasing thicknesses of materials, but much larger thicknesses of the absorbing substance are needed than were used for β-particles; many centimetres thickness of aluminium or millimetres to centimetres thickness of lead are needed. The results, like those in Expt. 131, show that the absorption of γ-rays by substances follows an exponential law. The coefficient of absorption and the half-value thickness may both be determined. The thickness of the absorber is again measured in mg/cm^2. A 5 μc Ra source may be used (Zita, MNU, XI/9, p. 423).

Expt. 134 (fig. 8.22). Ionizing radiations pass through a hole 1–4 mm^2 in a lead screen; they come from, e.g., a Leybold pin source or holder giving a path length of 3·38 cm for α-particles; they then pass through a strong magnetic or electric field and fall on a detector (zinc sulphide screen, counter tube or photographic film). This must be placed very close in for α-particles, but may be rather further away for β-particles. To obtain the strong magnetic field, two coils with 500 to 600 turns with a U-shaped yoke and pointed pole pieces may be used: and for the electric field a large plate capacitor with about 2 cm between the plates and a potential

difference of 3000–6000 volts. The deflection of α- and β-particles by magnetic and electric fields, using school apparatus, was first investigated by Herr Titgemeyer (PRAXIS, 1956/4, pp. 97 ff. and 1956/6, pp. 145 ff.). He came to the conclusion that in the magnetic

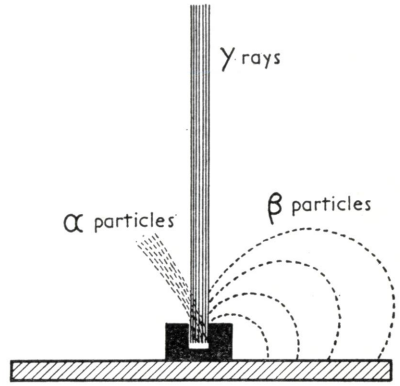


Fig. 8.22 Effect on α-, β-, and γ-rays of a magnetic field perpendicular to the plane of the diagram

field radiations with a long path-value must be used; that the deflecting field must cover the whole path; and that the strength of the magnetic field for α-particles must be about a hundred times greater than that for the fastest β-particles. It is very difficult to show electrostatic deflection of α-particles in schools; the field strengths available are sufficient only for slow β-particles.

Expt. 135. A strip of 35-mm photographic film is placed in a

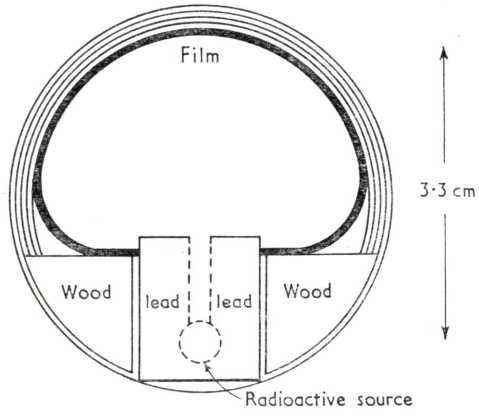


Fig. 8.23

casette as shown in fig. 8.23; a magnetic field is applied perpendicular to the plane of the diagram; and the film is exposed to the radiation from the source for about 36 hours. The film should then be completely, but not too strongly, developed (Rodinal 1 : 40). The results show the effect of those radiations which have passed through the magnetic field without deflection (the γ-component); a wider part, those which have been deflected a few millimetres to one side (the α-component); and on the other side a blurred blackening over a space of several centimetres, due to the β-particles. The experiment may be attempted with a 5 μc Ra source.

More detailed particulars of deflection experiments and a somewhat different arrangement are given by Titgemeyer, PRAXIS, 1956/4, p. 97 and 1956/6, p. 145.

EXPERIMENTS WITH α-PARTICLES

Expt. 136. The source of α-particles, e.g. 0·1 μc Pu 239 or 5 μc Am 241, is placed at various distances from a fluorescent screen; scintillations are seen. The eyes must be adapted to the dark before the experiment is begun.

Expt. 137. A source of α-particles, e.g. 0·1 μc Pu 239 or 5 μc Am 241, is placed inside the receiver of an air-pump at such a distance from a fluorescent screen that the α-particles just do not reach the screen. When the receiver is pumped out, scintillations become visible, but they disappear if the air is allowed in again. It follows that the path length of the α-particles is determined by their collisions with air molecules (Reimers, PRAXIS, 1952/3, p. 57).

Expt. 138. A *very* thin piece of aluminium foil (thickness <0·05 mm) is folded as in fig. 8.24 and placed between the fluorescent screen and the source of α-particles, e.g. 0·1 μc Pu 239 or 5 μc Am 241. The α-particles are completely absorbed by a definite thickness of the aluminium—about 0·05 mm. In the same way, the absorption in other substances, such as writing paper, wood, glass, etc., may be found. The short

Fig. 8.24

path-length serves to identify α-particles. Instead of the fluorescent screen one may use the spark counter due to Greinacher (see Expt. 104).

Expt. 139. A source of α-particles (a polonium pin source) is set up in front of the mica window of a Geiger counter. The pin must point directly at the counter, since the radiation is not equally powerful in all directions (this is evidently so, since from the construction of the source, the decay of particular atoms and their directions are not completely statistical). The source is now moved in small steps away from the mica window, and the corresponding counts are plotted on a graph against the distance between source and counter. The graph line is a descending curve. The fall is due not only to the energy which the α-particles lose when they strike molecules of air; the solid angle subtended at the counter also becomes smaller. The number of counts Z_g obtained at distance r_g must therefore be corrected by a factor $\frac{r_g^2}{r_b^2}$ obtained from a measured solid angle corresponding to a distance r_b. If the value $z_b = z_g \frac{r_g^2}{r_b^2}$ is now plotted against distance, one obtains a curve which lies parallel to the distance-axis almost as far as its end. The absolute value of the slope of this curve gives as its maximum the distance at which the majority of the α-particles lose their energy (the apparent or average range). The tangent at the turning point of the corrected curve gives at its intersection with the distance-axis the so-called extrapolated range. The air-equivalent of the mica window must also be added to the path length thus determined (Zita, MNU, XI/9, p. 419).

Expt. 140. A photographic plate is placed in the dark in a 1% solution of a thorium salt for 10 minutes, washed, and dried. It is left for some days in the dark, developed, fixed, washed, and dried. The plate is then examined under a high-power microscope. It shows star-shaped patterns, which are the tracks of α-particles. The length of these tracks can be measured with an eyepiece scale. The energies corresponding to the tracks shown on the photograph can then be looked up in tables and the radiating substances identified.

It is desirable to take microphotographs of the tracks. Leybold's special plates are to be recommended: British plates are now available, e.g. from Ilford or Kodak (T. A. H. Peacocke, SSR, 1954/127, p. 357).

range μ	*energy Mev*	*Parent substance*
22	5·42	Th 228
24	5·68	Ra 224
26·5	6·04	Bi 212
28	6·28	Rm 220
32	6·78	Po 216
47	8·78	Po 212
53	9·45	Po 212
63·5	10·62	Po 212

Expt. 141. For the visual observation of the α-decay of a gaseous radiation source, see also Expt. 115.

EXPERIMENTS WITH β-PARTICLES

Expt. 142. The apparatus and the method to be followed can be seen in fig. 8.25. The counting rate of the Geiger counter becomes

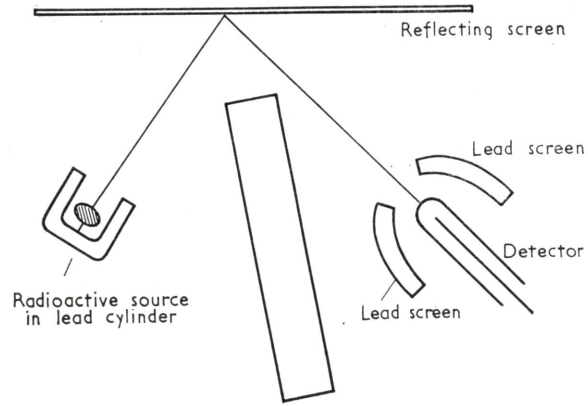


Fig. 8.25

greater as the atomic number of the atoms of the reflecting material increases.

Distances for the apparatus shown:

Distance from source to reflector 50 cm
,, ,, detector to reflector 50 cm
,, ,, detector to source 60 cm

Between the Geiger tube and the source is placed a pneumatic trough full of water, and about 20 cm wide.

Background count	38 counts/min.
Source	10 μc Sr 90/Y 90
Count without reflector	119 counts/min. (diffuse reflection from walls of room)
Count with reflector, Aluminium 0·5 mm thick	540 counts/min.

Expt. 143 (fig. 8.26). One, two, three, etc., thin pieces of equal thickness of glass, aluminium, etc., are placed over the opening in

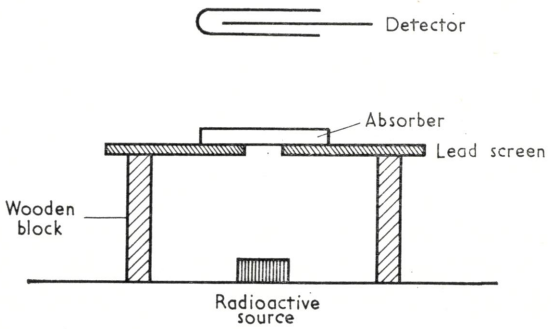


Fig. 8.26

the lead screen and the corresponding count numbers recorded. The count numbers are then plotted on semi-logarithmic paper against the thickness of the absorbing layers (in g/cm^2). If these absorbing layers are not too thick, the result is a straight line, from which the half-value thickness may easily be determined (the half-value thickness absorbs half the radiation).

Result: $A = A_0 e^{-kx}$ (x = thickness of absorber
k = mass absorption coefficient)

Remark on Expts. 130 and 131

If no so-called β-emitter is available (P 32 or Sr 90/Y 90) a result

for β-rays is still possible if first a measurement is made with $\beta + \gamma$-rays and then, by the use of a suitable filter, the β-rays are filtered out and the measurement repeated. The difference $(\beta + \gamma) - \gamma$ gives the required β-value.

Expt. 144. The apparatus is the same as that used in Expt. 143 for the absorption of β-rays. A piece of sheet rubber is used as the absorber. The detector is placed at such a distance that the number of counts per minute is not too high. If the rubber is then stretched the count frequency increases, since the elastic deformation reduces the thickness of the rubber. This procedure is used in industry in the manufacture of tinplate and of paper so as to maintain continuous control of the thickness of the product without either touching or destroying it.

Expt. 145. The radiation from a β-emitter is partly absorbed by increasing thicknesses of aluminium foil: the value of the transmitted radiation is plotted on semi-logarithmic paper against the thickness of the absorber. With β-emitting isotopes the result is a downward-sloping straight line: with radium, a mixture of several β-emitters (radium decay products), it is a curve made up of several almost straight lines. Step by step subtraction of the parts of the curve enables one to determine the absorption-coefficients and also the maximum range of each component part. This may also be done in the case of a mixture of artificial β-emitters. From these ranges and the empirical relation

$$E_0 = 1{\cdot}85R_0 + 0{\cdot}245 \quad (R_0 \text{ in g/cm}^2,\ E_0 \text{ in Mev})$$

the maximum energy of each β-component may be found: and then it is possible to identify them from tables of radioactive emitters (Ulbricht, PRAXIS, 1958/1, p. 1, and Zita, MNU, XI/9, p. 420).

Deflection of β-particles in a magnetic field

Expt. 146. A β-emitter (Sr 90/Y 90) giving about 10 μc is enclosed in a metal capsule which has an aluminium tube on one side (measurements given in fig. 8.27). This causes the β-particles to come out in a narrow beam. The end of this β-particle gun lies between the pole pieces of an electromagnet (two coils

each of 500 or 600 turns). Directly in the path of the rays, and at right angles to them, is a Geiger counter with its axis parallel to the lines of force between the pole pieces. The current in the electromagnet is switched on (about 1·5 amp) and the counter is

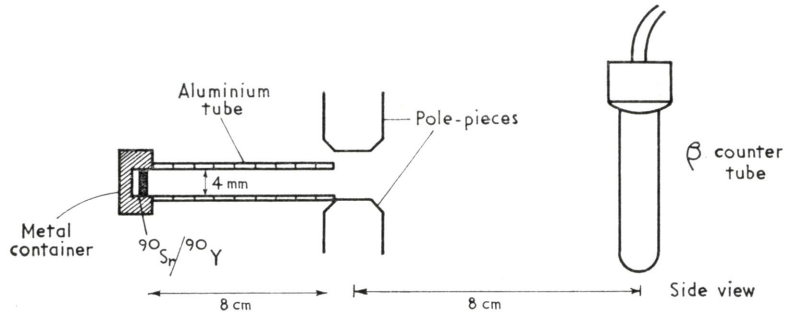


Fig. 8.27

moved in steps of 10° in an arc with centre at the pole pieces. The number of counts per minute is recorded for each position.

The values obtained are plotted on polar co-ordinate paper: this gives a record of the velocity (≙ energy) spectrum of the β-particles, since the slowest electrons are deflected most. Most of the electrons have a medium velocity. The results may also be plotted on linear paper against a scale of degrees: this is the usual way of representing the energy spectrum (principle of the β-spectrometer).

For demonstration purposes, the Geiger counter may just be moved in a line at right angles to the path of the β-particles. For example: Geiger tube FHZ69, distances as in Fig. 8.27. Background count 28 counts/min.

(i) Counter exactly in the direction of the β-particles: field off, 599 counts/min.

(ii) Counter exactly in the direction of the β-particles: field on 29 counts/min.

(iii) Counter tube moved at right angles: $d = 6$ cm, 307 counts/min.; $d = 5$ cm, 221 counts/min.

(iv) Field off. This experiment is the more convincing if the count rate is well above the background count. It is desirable to use an automatic counter or a rate meter. Although the electrons with maximum energy from the usual sources have a range of about 8 metres in air, it is desirable not to have the counter tube too

far away from the pole pieces, since the angle subtended by the counter tube becomes smaller as the distance increases. This entails a reduction in the number of counts per minute, especially of those due to the slowest electrons, which, however, are those of greatest interest in a demonstration of this effect.

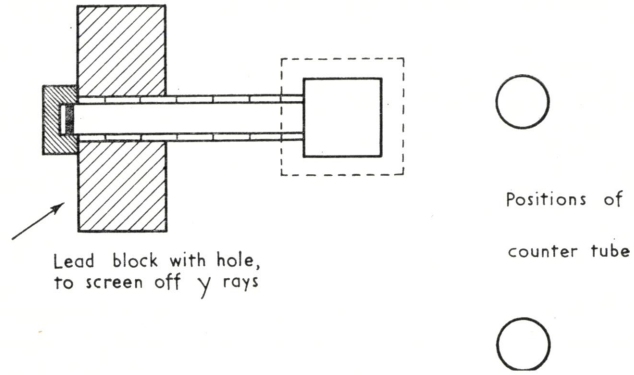


Fig. 8.28

The experiment may also be done with a point counter or a Wulf electroscope. (Also see Emeis, PRAXIS, 1958/12, p. 336.)

Expt. 147. A pure β-particle source is arranged in a tubular screen; with this the deflection of β-particles by a magnetic field may be demonstrated. A photographic plate is placed in the magnetic field so that the β-particles strike it: the exposure is continued for some days; then when the plate is developed the average radius of the path of the β-particles is determined. If the magnetic field strength is also known, then the energy of the electrons may be calculated from this radius and the field strength (Pohl gives a useful table in his *Electricity* for doing this). When the velocity of the electrons is calculated from the radius and field strength, given the rest-value of $\frac{e}{m_0}$, then an absurd value of the electron velocity is obtained, which is greater than the velocity of light. This shows that it is therefore necessary to take into account the relativistic increase of mass with velocity (Seus, PRAXIS, 1957/6, p. 145, and 1957/7, p. 184).

Expt. 148. The Lenard absorption law $I = I_0 e^{-ax}$ may be used as a basis for the determination of the cross-section of the atomic nucleus using fast and slow electrons; a is the total effective cross section Q. The effective cross section of one single atom is then $\frac{a}{N}$, where N is the number of atoms in 1 cm³. First the background current of one of the integrating circuits used in Expt. 110 is determined. Then a radioactive source is placed in front of the Geiger counter and the increase in current noted, I_0. This is repeated with an earthed piece of aluminium plate close in front of the counter, the increase is now I. From these results a may be calculated and hence the radius of an atom.

In the same way one may use the electrons from a Lenard tube. In determining the rate of decrease of the radiation in the air, the counter tube is placed about 6 cm from the Lenard tube and moved until the intensity I is only $\frac{I_0}{2}$. Then using a mean value 14·5 for the density of the air, one can obtain a value for the radius of atoms of air which is at least of the right order (Voit, PRAXIS, 1958/10, p. 261).

EXPERIMENTS WITH γ-RAYS

Expt. 149. The source, e.g. 5 μc Co 60, is placed at a distance of 1–2 metres from the detector—point counter or Geiger-Müller tube. The impulses are counted for a given time, e.g. 5 minutes. The source is then moved nearer to the detector in steps of 10 cm and the impulses are counted at each step for the same time. The results are shown in a table and then graphed.

From this it is evident that $Ir^2 =$ constant $=$ emission E.

Hence $$I = \frac{E}{r^2}$$

The detector should not be brought nearer than 20 or 30 cm, since at small distances errors will arise due to the length of the detector itself. If only a γ-source giving also strong β-radiation is available, then either a thick-walled counter must be used or the particles must be absorbed by a sheet of glass or Perspex in front of the source.

Absorption of γ-rays

Expt. 150. Apparatus and calculation are the same as for absorption of β-particles. If no source of pure γ-rays is available, e.g. Co 60 or I 131, then the β-particles from the source must be filtered out. As absorbers for γ-rays one may use lead plates, tiles, etc.

Result: γ-rays also have a half-value thickness, which depends on the energy of the rays. Compare Expt. 133.

Expt. 151. A simple Becquerel β-spectrometer, like that described in Expt. 132, and made from lead sheet 1·25 mm thick, is very suitable for a quantitative investigation of electrons produced by γ-rays (Compton, recoil, and photo-). The apparatus is placed in a homogeneous magnetic field, due to two coils of about 300 turns, with iron cores and pole pieces. The magnetic field causes a curvature of the path of the charged particles proportional to the quantity of their charges. Since the curvature is also proportional to the velocity (energy) of the particles, a Geiger counter with a mica window, placed at C, will record particles of a particular energy, depending on the strength of the magnetic field used. If the radius of curvature of the path and the strength of the magnetic field are known then

$$E = m_0c^2\{\sqrt{1 + (eB/m_0c^2)} - 1\}$$

A lead plate of not less than 1 mm thickness is placed between the radium source and the spectrometer, so as to absorb all the α- and β-particles. The Geiger counter will now show a relatively high 'background count', when the field coil current is zero: this is due to the γ-rays passing through the spectrometer. The current in the field coils is now slowly raised, and at particular values of the field sharp peaks will be noticed in the otherwise constant background mentioned above. From a knowledge of the relation between the current in the coils and the magnetic field strength, one can then plot a graph between the count frequency and the current strength, and graduate the abscissa axis according to the energy of the particles in MeV.

Expt. 152. The apparatus is the same as in Expt. 151. The direction of the magnetic field is arranged so that only particles with a

positive charge reach the Geiger counter. It will be seen that in this case only a single 'spectral line' stands out from the general γ-radiation: positrons with 0·36 MeV. These arise from γ-rays of 1·38 MeV by pair production. The corresponding electron energy of about 0·4 MeV may also be determined as in Expt. 151.

Expt. 153. If in setting up Expt. 152 one uses a γ-source whose radiations contain several components of clearly separated energies, then the positron spectrum will show energies E_1 of 1·02 MeV, and so on. It is therefore desirable to have between the source and the spectrometer only a thin lead foil to absorb the α-particles. The electrons of the β-radiation will then be deflected into the spectrometer when the polarity is reversed (Expts. 151 to 153: Zita, MNU, XII/2, p. 74).

FURTHER EXPERIMENTS WITH NATURALLY RADIOACTIVE SUBSTANCES

Decay of Pb 212 (Th B)

Expt. 154. 1 ml of a 1% solution of thorium nitrate has added to it 2 drops of 1% lead nitrate solution, 2 drops of barium nitrate solution, and some carbonate-free ammonia solution (0·88) so that precipitation is complete. This precipitate is then collected at the bottom of the test tube by any means available, e.g. any kind of centrifuge. The precipitate is coagulated by warming, and the supernatant liquid carefully decanted. The precipitate is then again dissolved in nitric acid and precipitated again. This operation is repeated again twice: finally the precipitate is washed on to a small filter paper with hot water and then dried with alcohol. Then it is transferred to a glass plate, e.g. a microscope slide and covered with Sellotape, so as to make it gas-tight. It consists of Th 232 and Th 228 as hydroxide, Ac 228 and Pb 212 of which the last is only fully precipitated in the presence of $Pb(NO_3)_2$ as carrier.

The β-activity of this precipitate is measured over a period of several days. If this activity is plotted on a graph against time, a curve like that shown in fig. 8.29 is obtained. The increase of the

activity towards the end of the lower curve is due to the formation of Ra 224 and hence Pb 212, from Th 228.

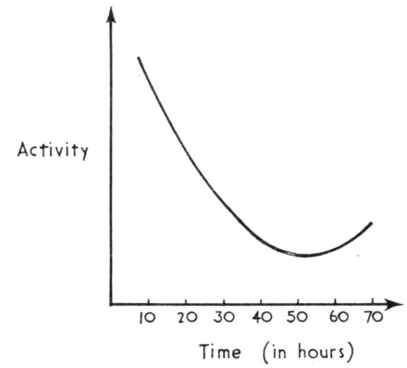


Fig. 8.29

Formation of Pb 212 (Th B)

Expt. 155. The liquid obtained at the first decanting in Expt. 154 is mixed with dilute sulphuric acid and the precipitate collected on a filter paper. It is washed and dried, and then placed on a glass plate: it is covered with Sellotape so as to be gas-tight. Ra 228 and Ra 224 are precipitated as sulphates being carried down by barium sulphate. The β-activity of the precipitate is measured for several days and plotted on a graph against time. A curve like that in fig. 8.30 is obtained. The curve shows the growth of Pb 212

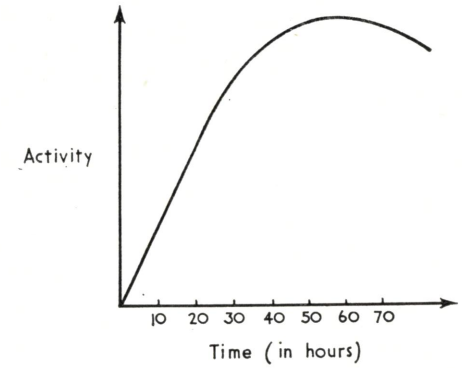


Fig. 8.30

from Ra 224. This reaches a maximum when Pb 212 has reached radioactive equilibrium with Ra 224. The curve then falls, due to the decay of Ra 224.

If appreciable quantities of Ra 228 are present, part of the growth curve will be due to the formation of Ac 228. The decay of Ra 228 with its half-life of 6·7 years is much slower than that of Ra 224 and this will cause the curve to fall more slowly from its maximum and eventually to reach an appreciably constant activity.

Decay of Bi 212

Expt. 156 (fig. 8.31). A platinum wire is fixed above some thorium hydroxide contained in a closed vessel made of a conducting

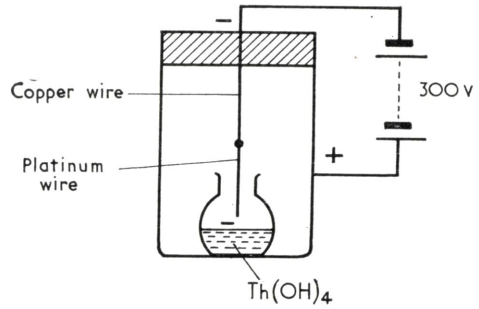


Fig. 8.31

material; the wire and the vessel are connected to a d.c. source of about 300 volts. Polonium 216 collects on the platinum wire (electron loss by recoil). This decays into Pb 212 after a half-life of 0·14 sec. Two days later the deposits have come to a state of radioactive equilibrium (in one hour sufficient deposit is obtained for use in a cloud chamber). The platinum wire is now immersed for about 5 minutes in 5 ml of hot, but not boiling, hydrochloric acid. The solution is now boiled for about 3 min, 2 drops of 1% lead nitrate solution are added and 2 drops of 1% bismuth nitrate solution followed by 2 volumes of distilled water and 2 volumes of 2N sulphuric acid and lastly topped up with an equal volume of alcohol. It is filtered and the bismuth in the filtrate is precipitated with H_2S, washed, and dried with alcohol. It is then mounted on a glass plate and covered with Sellotape. The activity is determined every 15 minutes over a long period, and the logarithm of the activity is plotted against time. Alternatively the activity may be plotted against time on semi-logarithmic paper. From the graph the half-life of about 60·5 minutes may be determined (Expts. 154 to 156: T. A. H. Peacocke, SSR, 1954/127, p. 363).

Activation of wires (with Th C and Th C′; also Ra C and Ra C′)

Expt. 157. A metal vessel contains some thorium oxide or pieces of incandescent mantle (for the decay products from thorium) or a radium salt or radium source (not mounted so that emanation cannot escape). Inside this vessel is placed a wire, insulated from the vessel and made negative by a potential of between 500 and 2000 volts. After a few hours the wire is covered with a thin layer of radioactive substances. The wire is wiped off with a linen rag or pocket handkerchief. The wiped-off deposit is brought in front of a Geiger counter. This procedure depends upon the fact that when an α-particle is emitted the decaying atom undergoes a recoil (conservation of momentum). It thereby acquires greater velocity and energy. Ra A, for example, has a recoil velocity of $3{\cdot}1 \times 10^7$ cm/sec and an energy of $1{\cdot}09 \times 10^5$ eV, which is about three million times its thermal energy. The atom may then hit nearby molecules and lose electrons at each impact, so that it is left as a positive ion; it can now be attracted by the negatively charged wire. A determination of the half-life makes it possible to identify the radiations.

Addendum. A long wire, made negative with respect to earth at about 100 volts, is exposed to the air for several days in a room; it is then wiped off with a pad of cotton wool. It can now be shown that the cotton wool has radioactive substances on it (T. A. H. Peacocke, SSR, 1954/27, p. 363, and Elster and Geitel, PHYS. Z. 3 (1902), p. 305).

Expt. 158. The linen rag of Expt. 157 is carefully incinerated and the ash, put in a packet of thin paper or cellophane, is brought near the Geiger counter. The conclusion is that incineration has no effect on radioactivity (Seus, PRAXIS, 1956/12, p. 323).

Naturally occurring light radioactive elements

Expt. 159. It may be established, by means of sufficiently sensitive apparatus (a Geiger-Müller counter), that potassium and rubidium (the first plays a prominent part in human metabolism)

have naturally occurring radioactive isotopes (K 40 and Rb 87 are β-emitters).

Compounds containing these elements may be used, e.g. KCl or a rubidium salt.

EXPERIMENTS WITH NEUTRONS

Note. Whilst the use of neutron sources is not entirely forbidden in British schools, the Ministry of Science and Education gives no encouragement to teachers to ask for them, and there are very special regulations governing their use. At present one or two schools have been allowed to install one, under the supervision of the Radiological Protection Service, but it is not expected that any more will be authorized for some time to come, if at all.

Experiments which require the use of a neutron source are thought to be unnecessary in British schools and have been included only because firstly they are given in the original German text and secondly because the book may be found of interest in institutions carrying out experiments at higher than school level.

For the following experiments one needs a neutron source, containing at least 1 milligram of radium enclosed with some beryllium in a metal tube. Neutron sources giving little γ-radiation would be preferable, but they have other more serious disadvantages. A polonium, beryllium neutron source has a half-life of only 138 days; a radium D-beryllium source, with the favourable half-life of 25 years, is out of the question in most cases on account of its considerably higher price. The radium-beryllium source must be kept in a lead container because of the γ-rays it emits; and this must be surrounded by a thickness of about 5–8 cm of paraffin wax to slow down the fast neutrons. The container for the paraffin may be a thin-walled steel can to ensure safety. The thermal neutrons which diffuse through the steel can, may be absorbed if the can is placed in a tank containing a solution of borax. Ready-enclosed neutron sources may be obtained from various scientific supply firms; some of these sources may have greater activity than that described.

In a neutron source, the following reaction takes place:

$$^{9}_{4}\mathrm{Be} + \alpha \rightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{0}n$$

The maximum energy of the neutrons is 13·7 MeV.

The fast neutrons are slowed down by collision with the protons of the paraffin and lose their energy until they have the same energy as the remainder (thermal neutrons).

Expt. 160. The neutron source in its paraffin sheath is put into a container made of thin rhodium foil. The rhodium is exposed to the neutrons for 5 minutes and is then put over a Geiger-Müller counter. The count obtained is distinctly greater than the background count. The reaction takes place thus:

$$^{103}_{45}\mathrm{Rh} + {}^{1}_{0}n \rightarrow {}^{104}_{45}\mathrm{Rh} \qquad {}^{104}_{45}\mathrm{Rh} \rightarrow {}^{104}_{46}\mathrm{Pd} + \gamma + e^{-}$$

The $^{104}_{45}$Rh decays, with a half-life of about 42 sec into $^{104}_{46}$Pd.

Expt. 161. The rhodium foil is activated as in the preceding experiment and placed over the Geiger tube. The counts are now noted at intervals of 20 or 30 sec; the logarithms of the counts are graphed against time. The half-life may be determined from the straight line which can be drawn through the points.

Expt. 162. The rhodium foil is placed round the neutron source and is surrounded by cadmium foil. The whole is then placed in a cylinder of paraffin wax. The rhodium foil is tested at the Geiger tube after about 5 min; hardly any activity is found. Hence it may be concluded that the cadmium foil is a good absorber for slow neutrons and that the rhodium foil was activated by thermal neutrons and not by fast ones.

Alternatively, instead of cadmium foil, boron is very suitable as an absorber for slow neutrons. This may be used in the form of fine boron carbide powder dusted on to thin cardboard and then coated with shellac varnish. After this has dried, and the surplus boron carbide has been brushed off, the treated cardboard may be used as a 'neutron absorber'.

Expt. 163. The rhodium foil in Expt. 139 is wrapped in lead foil instead of cadmium foil. The rhodium is found to be activated. Lead is permeable by both fast and slow neutrons.

Expt. 164. A few cm^3 of sodium chloride solution are irradiated by a neutron source for two or three days. The neutron source should not, however, be placed directly in the solution as the danger

of corrosion causing leakage of the neutron source is too great. The solution is thereby activated. The following reaction takes place:

$$^{23}_{11}\mathrm{Na} + ^{1}_{0}n \longrightarrow ^{24}_{11}\mathrm{Na}$$

$^{24}_{11}$Na decays with a half-life of 15 hours.

$$^{24}_{11}\mathrm{Na} \longrightarrow ^{24}_{12}\mathrm{Mg} + \gamma + e^{-}$$

Expt. 165. Activated sodium chloride solution, as in the preceding experiment, is reduced in volume by boiling and then converted into sodium sulphate by means of sulphuric acid. This sulphate is then found to show activity, so it is the sodium and not the chlorine which has been activated.

Expt. 166. Expts. 160 to 163 may also be performed with indium foil. The time for which the activity lasts will then be about 2–3 hours.

(Expts. 160 to 166 are due to Herr Seus, PRAXIS, 1956/10, pp. 265 to 269, and PRAXIS, 1957/6, p. 145. See also Schupelius, MNU, XI/3, p. 122.)

Expt. 167. Manganese compounds and metallic manganese may also be activated; the half-life of the reaction products is about 2·6 hours, and the useful activity lasts for at least 8 hours (Wiebe, PRAXIS, 1958/10, p. 264).

Expt. 168. When rhodium foil is activated by slow neutrons, as in Expts. 160 to 163, the quantitative evaluation of the decay of activity when graphed on semi-logarithmic paper gives not a straight line but a curve which may be regarded as the sum of two straight lines, corresponding to half-lives of about 50 sec and 4·3 min respectively. Since the rhodium foil used was a pure isotope (Rh 103) this means that isomeric nuclei have been produced (Saur, PRAXIS, 1957/8, p. 209).

Expt. 169. The neutron source, with its lead case open, is placed near a cloud chamber, so that the opening points towards the chamber. A slab of paraffin wax about $\frac{1}{2}$ cm thick is placed in the cloud chamber. The neutrons cause protons to be ejected from the paraffin by recoil, and these are visible in the cloud chamber as

ionizing particles. If the cloud chamber has Perspex sides, protons will be ejected from these (Seus, PRAXIS, 1956/10, pp. 265 to 269).

Transformation of $^{127}_{53}$I by thermal neutrons (Szilard and Chalmers)

Expt. 170. Ethyliodide (C_2H_5I) is irradiated by slow neutrons for 1–1$\frac{1}{2}$ hours in a pharmaceutical tablet tube (see Expt. 164). The iodide reacts as follows:

$$^{127}_{53}\mathrm{I} + ^{1}_{0}n \longrightarrow ^{128}_{53}\mathrm{I} \qquad ^{128}_{53}\mathrm{I} \longrightarrow ^{128}_{53}\mathrm{I} + \gamma \qquad ^{128}_{53}\mathrm{I} \longrightarrow ^{128}_{54}\mathrm{Xe} + e^{-}$$

An excited compound nucleus is formed first, which emits a γ-quantum and is transformed into the β-emitting iodine isotope $^{128}_{53}$I. The end product is $^{128}_{54}$Xe (Xenon). The half-life of $^{128}_{53}$I is about 25 minutes. When the activated I atom emits the γ-quantum, it undergoes a recoil which is powerful enough to tear the iodine atom out of the molecule. There are therefore free iodine atoms in the liquid. The contents of the tablet tube are then poured into a charcoal filter (e.g. Filter No. 508, Schleicher and Schüll Ltd), or a white filter paper dusted with charcoal. The free iodine is absorbed by the charcoal. The filter is dried and its activity may then be measured conveniently by means of a β-counter tube. The half-life of the $^{128}_{53}$I is determined in the usual way (see Expt. 116).

The experiment can also be performed with ethylmonobromide (C_2H_5Br) or ethyldibromide ($C_2H_4Br_2$). The half-life of the radioactive $^{80}_{35}$Br thus produced is about 18 minutes (Seus, PRAXIS, 1957/2, pp. 37 ff.).

Expt. 171. Several test-tubes containing the same quantity of ethyl iodide are exposed for different lengths of time to the same neutron flux. The contents of each tube are then passed through a separate charcoal filter. After being dried, each filter is placed round a Geiger tube after an equal time, reckoned from the cessation of activation. The counting is then allowed to take place for equal times. An activation curve may then be plotted if the count rate is plotted against the activation time.

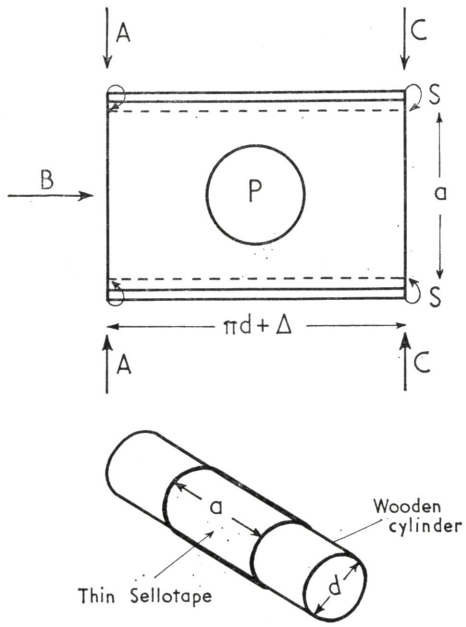
FURTHER EXPERIMENTS WITH ARTIFICIAL ISOTOPES

Expt. 172. For experiments on fall-out from radioactivity, specimens of 250 cm^3 of snow or rain are first filtered through a very

thick filter with a low ash content (e.g. Whatman No. 42), and rinsed with distilled water so as to wash any other soluble components into the solution. The filter is then completely incinerated. The ash is then transferred to a container with a little HCl or HNO_3 and evaporated down. The filtrate is also evaporated, but it is best to blow on its surface with a fan so as to avoid any spurting. It is transferred to a container by means of HCl or HNO_3 and evaporated.

The results obtained are then shown either in counts/min against the quantity of fall-out material in l on which the measurement was based, and checked over a longer period of time, or the series of measurements is calibrated in μc by means of K 40. The β-radiation from K 40 is used for comparison with the activity of the fall-out, since the average β-activity of the two is of the same order.

The K 40 contained in 1 g of potassium sulphate corresponds to an activity of $3{\cdot}7 \times 10^{-4}$ μc. For the calibration of a Geiger tube assembly it is necessary that the geometry of the K 40 standard



a = length of effective volume of countertube
d = outside diameter of countertube
P = radioactive source
S = fold, turned backwards to strengthen the edge

Rectangle $a(\pi d + \Delta)$ active side outwards

Put together by rolling round the cylinder so that CC overlaps AA, and secure loosely with Sellotape. Then slide it off the cylinder

Fig. 8.32

radioactive source shall be exactly the same as that of the source to be compared with it. The geometry factor of the apparatus is found from the count obtained and from the known activity of the standard. Small capsules may be used as containers for the sources: an end window Geiger tube must then be used. It is, however, better to use a cylinder of aluminium foil, which can be placed over the counter tube. The construction of this cylinder is shown in fig. 8.32. Such a cylinder ensures that the largest possible portion of the reacting part of the Geiger tube is brought into use. A not so small activity is, however, best measured by means of a lead vessel with walls about 5 cm thick, with a lining of iron or brass. It is also interesting to dry a filter before incinerating it and to prepare an auto-radiograph from it (Diehl/Setter, *The Science Teacher*, Vol. 25, No. 2, p. 80: Kraemer, PRAXIS, 1958/1, p. 15; Seus, PRAXIS, 1958/3, p. 65).

Expt. 173. The activity of grass may be determined by a method similar to that of Expt. 172. A suitable amount is first dried in an oven, and then completely incinerated in a closed crucible. The ash is transferred to a source-container by means of a few drops of *n*-HCl, *n*-HNO_3 and water, and is then evaporated to dryness. The results are shown either as counts per minute and grams, or after being expressed as μc/g, on semi-logarithmic paper; the decrease in activity with time is determined (Diehl/Setter, *The Science Teacher*, Vol. 25, No. 2, p. 77).

Expt. 174. An experimental determination of the activity of the air may be made by means of a cardboard tube or box closed at one end with fine mesh wire gauze; the other end has a connection for vacuum cleaner or air pump. A filter is placed over the gauze and held in place by rubber bands. Paper handkerchiefs are suitable as filters for use for simple qualitative work or for autoradiographs of the filter. For quantitative determinations use the cellulose-asbestos filters, i.e. toughened ones. A vacuum cleaner is not suitable for these last filters; a vacuum pump should be used.

When enough air has been aspirated through the filter, it is taken off and placed round a Geiger tube. When this is being done, the Geiger tube must either be protected by a thin foil or the dust layer is removed with some filter material.

In the air there is present a mixture of natural (mostly short-life) and artificial (usually long-life) radioactive substances. The longer the process of aspiration, the more of the long-life substances will be collected. If the long-life fission products are to be studied, then specially long aspiration-times will be needed.

Radon daughter products are spread over a few hours; thoron daughter products over two or three days. Radon daughter products have a half-life of about 30 min; those from thoron are identified by a half-life of about 10 hours. The residual activity left after the decay of these sources is in general due to artificial radioactivity. A determination of the age of these sources is not however possible because the air may contain many very old fission products. It is attractive sometimes to prepare an auto-radiograph from a filter. Quite often there appears on the radiograph the trace of a 'hot particle'. This may then be removed from the filter, and with sufficiently sensitive apparatus, the half-life of the particle may be determined.

Separation by diffusion

Expt. 175 (fig. 8.33). Diffusion experiment with H_2 (porous pot). A rapid stream of hydrogen is passed up into the beaker:

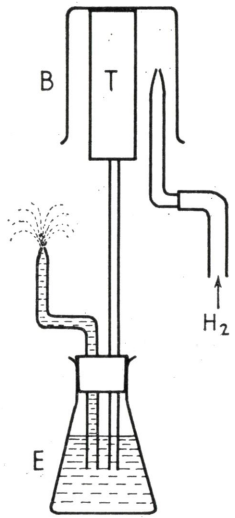


Fig. 8.33

molecules of this gas pass into the flask more rapidly than those of air flow out and the increase in pressure forces the water out through the delivery tube in a fountain. If the beaker is removed, the water rises into porous pot *T*, owing to the decrease in pressure in the pot.

Expt. 176. Separation by chromatography. Two cuts are made in a piece of a filter paper, as shown in fig. 8.34: the strip between the cuts is bent downwards, and the filter paper is then put across the top of a beaker or a flat dish, so that the bottom of the strip is immersed in the liquid. One or two thin glass rods are placed between the filter and the edge of the glass so that the filter shall not sag down. If different substances, notably organic dyestuffs, have been dissolved in the liquid, then after some time a difference in their speeds of ascent will become evident (Siemon, PRAXIS, 1953/11 and 1955/5).

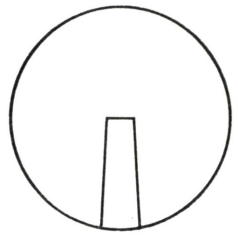


Fig. 8.34

Expt. 177. Separation by thermal diffusion.

A heater wire is fixed along the axis of a closed glass tube about 80 cm long. The tube is fixed vertically and is filled with a mixture of helium and carbon dioxide: the wire is brought up to a low red heat; after a short time a separation of the two gases takes place, which is made evident by their different thermal conductivities. The lower part of the wire glows more brightly, whilst the upper part is darker. The lighter gas rises near the heater wire: the heavier one sinks near the cold sides of the glass.

The rate of separation may be increased by a factor of about two if a 50/50 mixture by volume of hydrogen and carbon dioxide is used (Vatter, PRAXIS, 1956, Vol. 7, p. 173).

Other methods of separation are:

(i) *By electrolysis.* The electrolysis of acidulated water causes a separation of the lighter ordinary water from heavy water.

(ii) *By evaporation.* Ordinary water is evaporated more easily than heavy water.

(iii) *By centrifuging.*

(iv) *By chemical reaction* (different reaction equilibria).

(v) *By mass spectrography.* The separation of isotopes is carried out mainly by this last method.

Experimental analogy for the illustration of nuclear forces

In this the electrical forces are simulated by magnetic fields, and protons by small bar magnets 35 mm long and 5 mm in diameter. Seven such magnets are needed.

Expt. 178. Six of the small magnets are fixed to the upper ends of springy pieces of steel wire (knitting needles) about 0·7 mm in diameter and 150 mm long. These needles are stuck into wood or cork so as to form a ring of diameter about 60 mm: the height of the upper ends of the magnets should be about 145 mm. The poles of all the magnets are arranged so that they repel one another. The seventh magnet hangs in the middle of the ring from an aluminium wire 1 mm thick, which is attached at the top to silk fibres supported by a retort stand so that the magnet can swing pendulum-wise; the lower pole of the swinging magnet should just clear the top poles of the other six. The pendulum magnet is made to swing, with greater or smaller velocity, towards the others; the various effects obtained will illustrate the potential wall, the tunnel effect, etc.

If the top ends of the lower magnets and the lower end of the pendulum magnet are coated with luminous paint and the experiment is then done with the paint brilliantly illuminated in a darkened room, the coated ends of the magnets will look like small particles (Wilner, Stockholm, PRAXIS, 1953/6, p. 186).

Auto-radiography

Expt. 179. A radioactive source, such as pitchblende, luminous clockhand, gas mantle, etc., is placed on the film side of a photographic plate; this is done in a light-tight box in a dark room. The source is left on the plate in the box for several days. The plate is then developed, and is found to be blackened where radiations have struck the film. If, however, the plate is wrapped in light-tight paper, and the source laid on that, then the strongly ionizing, and therefore very actinic, α-rays can no longer reach the plate. Only β- and γ-rays can now do so, and in this case the time of exposure must be very much longer (Melcher/Gläser, PRAXIS, 1959/8, p. 219).

Index